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ICE MANAGEMENT IN THUNDER BAY HARBOUR
WINTER 1984
SUMMARY REPORT

PREPARED FOR:

TRANSPORTATION DEVELOPMENT CENTRE,
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JANUARY 1985

BY

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17. Abstract

This report describes the results of a research program carried out in Thunder Bay Harbour during winter 1984. The program consisted of two separate experiments.

The first experiment evaluated the use of an air cannon bubbler system for ice suppression. Air and water temperatures, ice thickness and ice cover area, and ice melting mechanisms were monitored along with the rate of ice clearing using a 10-unit air cannon bubbler system. The air cannon system was faster and more efficient at melting ice than other systems at Thunder Bay. It was also more economical. The rate of ice melting by the cannon bubbler system was not limited by the initial water temperature in the slip.

The second experiment measured and compared forces exerted on a dock wall by an icebreaking vessel entering a slip with an intact level ice sheet and by the vessel when fitted with an air cushion icebreaking bow (ACIB). Ice forces exceeded 184 kN/m with the icebreaker alone, while a maximum force of 178 kN/m was recorded with the ship and ACIB comination. It was concluded that while the icebreaker alone should not be used to clear intact ice in the slip, the ACIB/icebreaker combination can result in an effective system.

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17. Résumé

Ce rapport rend compte des résultats d'un programme de recherche sur la maîtrise des glace; composé de deux volets, il a été au cours de l'hiver 1984 dans le port de Thunder Bay.

Le premier volet concernait l'évaluation d'un ensemble de 10 mélangeurs à canon pneumatique utilisés pour faire fondre la glace. Les chercheurs ont mesuré les débits d'air, la température de l'eau, l'épaisseur de la glace, la superficie de la zone déglacée, la vitesse de déglaçage, et ont observé les mécanismes de la fonte de la glace. Ce système s'est révélé plus rapide et plus efficace que les autres systèmes mis en oeuvre à Thunder Bay, en plus d'être plus économique. À remarquer que la température initiale de l'eau dans le bassin n'a pas ralenti l'action des mélangeurs essayés.

Le deuxième volet intéressait la mesure des forces exercées par les glaces sur les parois d'un bassin de chargement au cours d'opérations de déglaçage par un brise-glace couplé ou non à une plate-forme à coussin d'air. Agissant seul dans une glace uniforme intacte au départ, le brise-glace a induit un force maximum dépassant 184 KN/m, alors que cette force ne dépassait pas 178 KN/m lorsque le brise-glace était couplé à la plate-forme à coussin d'air. Conclusion: les brise-glace ne devraient jamais procéder seuls au déglaçage des bassins portuaires, le tandem brise-glace/plate-forme à coussin d'air ayant fait la preuve de son efficacité.

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FOREWORD

A significant effort has been made by Transport Canada, during recent years, to investigate an ice management system that will achieve a guaranteed opening date for Thunder Bay's Lakehead Harbour shipping season.

To guarantee the opening of the navigation season by the 1st of April each year, ice management systems have been investigated. These projects have included the development of an air cushion icebreaking bow (ACIB), the installation of various conventional bubbler systems, and installation of a cannon bubbler developed by Atara Corporation. Measurement of water temperatures in various slips, a review of various ice management alternatives and an evaluation of ice management techniques has been carried out.

This report describes the results of a research program carried out in Thunder Bay Harbour. The program consisted of two separate experiments. The first evaluated the use of the cannon bubbler for ice suppression [1]. The second experiment measured the forces exerted on the dock wall during entrance of an icebreaking vessel into the slip in the presence of an intact level ice sheet [2].

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1. INTRODUCTION

A significant effort has been made by Transport Canada, during recent years, to investigate an ice management system that will achieve a guaranteed opening date of Thunder Bay's Lakehead Harbour shipping season.

The harbour is located in the North West side of Lake Superior (see Figure 1.1), and is the most northerly port on the St. Lawrence Seaway. During winter, the average ice cover thickness is expected to grow to about 0.75 m. Freezeup occurs in early December and natural breakup dates fluctuate between the middle and end of April. During the last 30 years, the opening date of the harbour ranged between the 25th of March and the 20th of April, depending greatly on the severity of the winter and the method used for breaking and clearing the ice in the harbour.

The recent increase in tonnage handled by the terminal, from 12 million tons in 1977 to almost 20 million tons in 1984, resulted in significant pressure on the responsible authority to increase the capacity of the terminal. One of the solutions proposed to solve this problem, was to guarantee the opening of the terminal following the ice season at a prefixed date. This will reduce the uncertainty in scheduling the facilities and, of course, result in an improvement to the overall efficiency of the harbour.

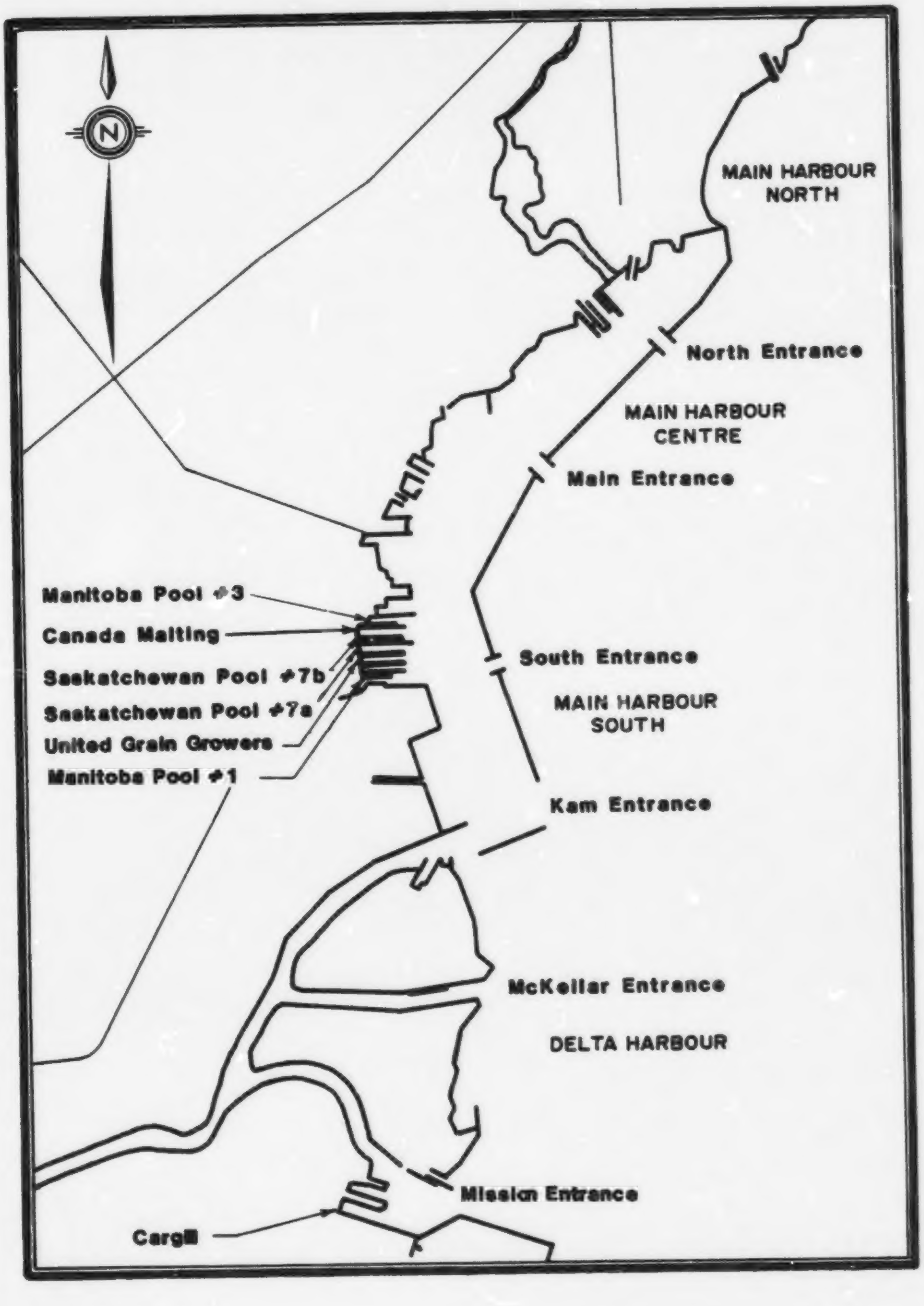
Ice management techniques to break the ice in the harbour outside the slips have been relatively successful. The Canadian Coast Guard Icebreaker "ALEXANDER HENRY" has been used to break the ice, and when the wind direction becomes North or North-Westerly, the broken ice has been blown out of the harbour. Most recently, the use of the ACIB notched to the ALEXANDER HENRY has provided a significant improvement in her capability to break in level ice, thus reducing the time required for this task.

Many studies have been carried out to solve the problems of navigation inside the slip while a relatively intact ice cover is still present.

To guarantee the opening of the navigation season by the 1st of April each year, ice management systems were investigated. The most important development was in Thunder Bay Harbour where several research studies were carried out. These projects included: the development of an air cushion icebreaking bow (ACIB), the installation of various conventional bubbler systems (Hill [3] and Kamo et al [4, 5]), the installation of a cannon bubbler developed by Atara Corporation [6], the measurement of water temperatures in various slips [7], the review of various ice management alternatives [8], and ice management techniques evaluation [9].

FIGURE 1.1

THUNDER BAY HARBOUR


N
MAIN HARBOUR NORTH
North Entrance
MAIN HARBOUR CENTRE
Main Entrance
Manitoba Pool #3
Canada Malting
Saskatchewan Pool #7b
Saskatchewan Pool #7a
United Grain Growers
Manitoba Pool #1
South Entrance
MAIN HARBOUR SOUTH
Kam Entrance
McKellar Entrance
DELTA HARBOUR
Mission Entrance
Cargill
0 .5 1 2 KM

2. OBJECTIVES

The overall objectives of this program were to achieve a guaranteed opening of Thunder Bay Harbour by the 1st of April each year.

The objectives of this experimental program were:

1. To evaluate the effectiveness of a series of air cannon bubblers with deflectors installed, in developing horizontal flow capable of melting the ice cover in one of Thunder Bay Harbour's slips, and compare the results with other systems deployed in the same area.
2. To measure the ice forces exerted on the grain elevator structure foundations and its associated motion resulting from the movement of an icebreaking vessel inside the slip. Real time comparison of the allowable calculated forces and the measured forces were to be made to ensure that the exerted forces would not exceed 20% of the allowable forces.

3. TEST PROGRAM

The field test program consisted of two separate experiments carried out in Thunder Bay Harbour between February and March 1984. The first experiment was the deployment and monitoring of ten air cannon bubblers between the 9th and 21st of March. The test location was between Canada Malting and Saskatchewan Pool 7b grain elevator slip.

The test involved operating the cannon bubbler system with controlled air flow and a variety of deflectors while monitoring environmental parameters and ice suppression or melting rate.

The second experiment was carried out to measure ice forces on both docks adjacent to the United Grain Growers and Manitoba Pool #1 grain elevators. The dock and grain elevators were instrumented to measure force and motion.

The ALEXANDER HENRY icebreaker, with and without the ACIB system, was used. This vessel alone has a conventional bow that does not promote the downward breaking of ice and tends to break the ice by crushing and splitting. The use of the ACIB notched to its bow is believed to generate considerably less horizontal forces due to the different mode of icebreaking.

The first test was carried out using the ALEXANDER HENRY alone. The icebreaker approached the slip by ramming in about 0.7m thick ice. Due to continuously increasing pressure on the dock, the test was aborted. The icebreaker was about 50m from the entrance of the slip when the test was stopped.

The second test was carried out after coupling the ACIB to the ALEXANDER HENRY. At that time, the ice pressures were lower and the test continued until approximately 20m of ice in the slip was broken. The test was aborted when the ice stopped breaking due to insufficient pressure developed by the ACIB for breaking thicker ice in the slip.

The final test occurred three days later using the ALEXANDER HENRY notched to the ACIB. For this test, the Hexpack pressure transducers were relocated along a longer length of the dock permitting the icebreaker to break the ice in the entire slip.

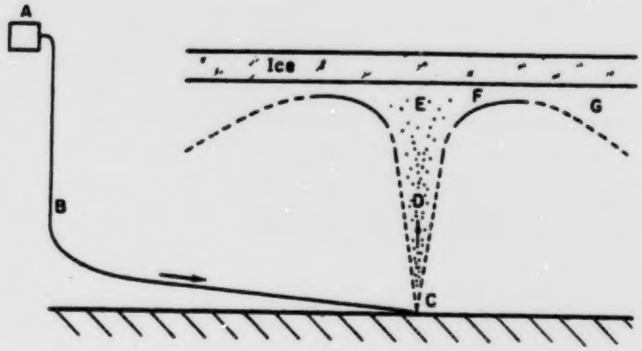
3.1 Air Cannon Bubbler Experiment

Theory

A general model for the operation of a point source bubbler is shown in Figure 3.1 [10]. A bubbler stream forms at the orifice (C), and rises in a plume. The plume expands linearly with height, expanding the radius of entrained water (D). The plume expands laterally at the surface and creates a convection cell which maintains a flow of warm water to the surface (E, F, G). Ashton derived models relating the radius of induced flow at the surface, the centreline velocity of the plume and the induced discharge at the surface to the orifice depth and air discharge, for a point source or line bubbler [10].

FIGURE 3.1

SCHEMATIC DIAGRAM of the DIFFUSER BUBBLER SYSTEM OPERATION



(AFTER ASHTON [10])

A -COMPRESSOR
B -AIR SUPPLY LINE
C -DIFFUSER LINE
D -RISING PLUME OF ENTRAINED WATER
E -PLUME SPREADS UNDER ICE SURFACE
F -REGION OF HORIZONTAL FLOW OF PLUME
G -DISSIPATION OF ENTRAINED WATER

The "burper" type of air cannon bubbler used in this test differs in two ways from the conventional bubbler described above. First, air is emitted by an accumulator or burper periodically as a single, large bubble rather than as a stream of small bubbles. Second, the bubbles are emitted into a tube or cannon which confines the bubble plume. The large bubble then acts as a piston to move the water column through the tube.

A theoretical model is not available for air cannon bubbler, but results from laboratory tests and theoretical calculations [11],indicate that the cannon bubbler should be more efficient at suppressing ice than any of the other types of bubblers.

Theoretical reasons for superiority of the cannon bubbler include:

- faster rising velocity for the "burper" type air cannon bubbler due to larger bubble radius.
- improved efficiency of entrainment in the confined cannon duct as compared with the rising plume of a conventional bubbler.
- efficient use of energy when a deflector is used to direct the horizontal flow of the air cannon bubbler.
- higher coefficient of heat transfer due to the higher current velocity and Reynold's number.

Instrumentation

The 1984 tests involved installation of an air cannon bubbler system and thermistor arrays, manual measurement of ice thickness and ice temperature, and air photography of ice cover extent.

The bubblers tested during this program were the "burper" type air cannons manufactured by Atara Corporation. Basic components of the bubblers are shown in Figure 3.2. The cannon bubblers were fitted with one of three types of deflectors; cone, elbow or elbow with internal baffle.

An array of ten cannon bubblers was used in the tests, with seven located along the north slip wall and three in the centre. Instrument location is shown in Figure 3.3.

Bubblers were installed by cutting a 1.2 m square hole in the ice cover and sinking the bubblers with a steel plate anchor.

Air was supplied from a central blower via a flexible hose. A 20 HP, 575 volt blower maintained a system pressure of 76 kPa (11 psi) at 0.132 m^3/s (280 SCFM), or 0.0132 m^3/s per bubbler. Air was supplied to the bubbler system from the morning of March 9th until March 22nd, 1984.

FIGURE 3.2

ATARA AIR CANNON BUBBLER TYPICAL INSTALLATION

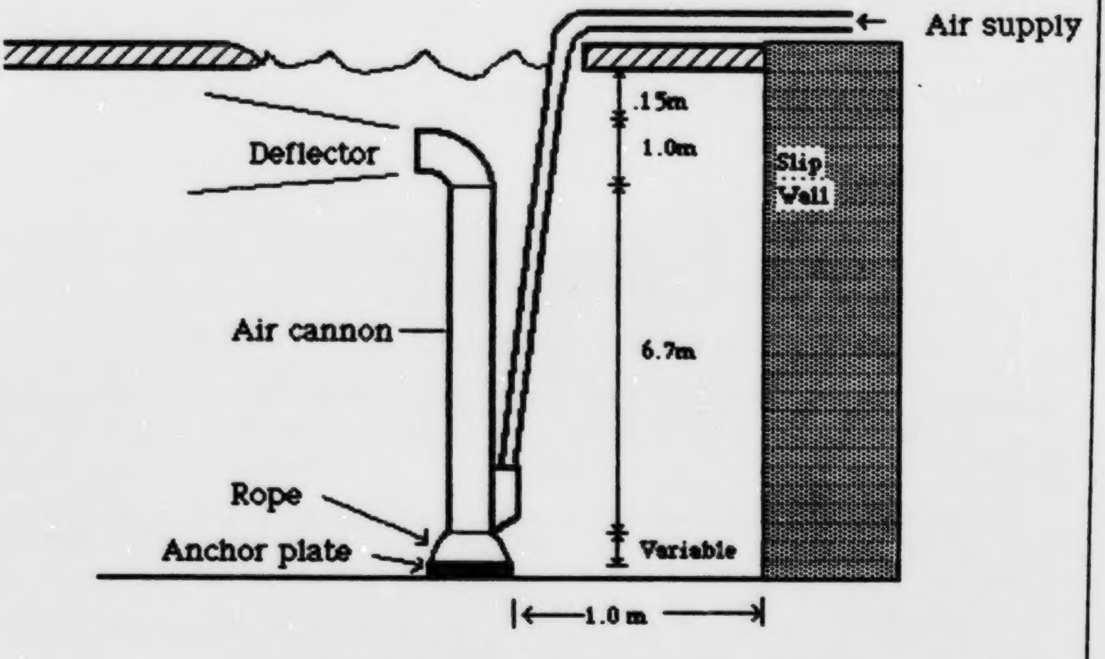
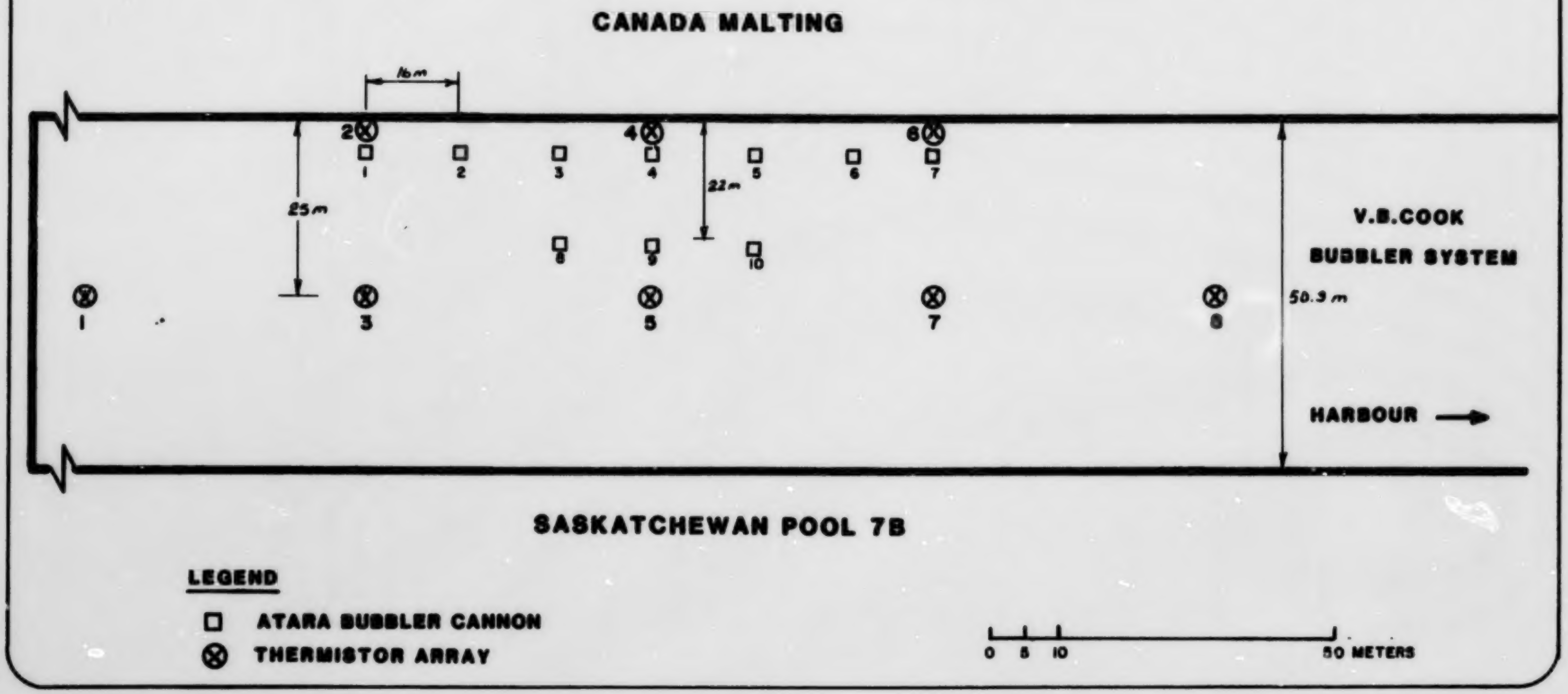

Air supply
.15m
1.0m
Deflector
Slip
Wall
Air cannon
6.7m
Rope
Anchor plate
Variable
1.0 m

FIGURE 3.3

INSTRUMENT LOCATION

CANADA MALTING/SASKATCHEWAN 7B SLIP


CANADA MALTING
16m
2
4
6
1
2
3
4
5
6
7
22m
25m
8
9
10
1
3
5
7
8
V.B.COOK
BUBBLER SYSTEM
50.3 m
HARBOUR →
SASKATCHEWAN POOL 7B
LEGEND
☐ ATARA BUBBLER CANNON
⊗ THERMISTOR ARRAY
0
5
10
50 METERS

Water and air temperatures were measured using eight thermistor arrays of three or four thermistors per string, located as shown in Figure 3.3 Thermistor data were recorded at half hour intervals from March 8th until March 10th, and then at two hour intervals until March 23rd. Data were recorded directly onto floppy discs using a portable data acquisition system.

Ice suppressions were monitored by manually measuring thickness on March 8th, and from vertical air photographs taken at 0900 hours on March 9th, 12th, 14th, 16th, 19th, 21st, 23rd, and 26th.

Ice temperatures were measured at an adjacent slip and are applicable to the Canada Malting slip.

3.2 Dock Load Experiment

Experiment Preparations

Before the start of the tests, the dock structure and foundation were analysed to estimate a maximum safe lateral and perpendicular load that the ice could exert before causing damage. These results showed that the maximum safe load, both parallel and perpendicular to the dock face, is 365 kN/m. This maximum load is located approximately midway along the length of the dock at the Workhouse.

The estimation of forces applied to the dock during the penetration of the ALEXANDER HENRY, were calculated using a finite element model. For this computer model, conservative approximations were made. First, it was assumed that the ALEXANDER HENRY would enter the slip without the assistance of the ACIB. When the ACIB is used, the loads are considered to be lower. Second, an ice thickness of 1 m was used in the math model when it was expected that the ice thickness would be less. Finally, it was assumed that the dock would be infinitely rigid, although a second scenario was used giving the dock a spring constant of 0.7 mm/kN. Predicted by the math model, the maximum dock load was 87.8 kN/m for an infinitely rigid structure and 3.0 kN/m using a spring constant of 0.7 mm/kN. It was expected that the measured loads should have fallen in this range.

The estimation of the building acceleration due to the impact of the ALEXANDER HENRY with nearby ice, was performed using another finite element model. The problem was simplified by making a conservative approximation for the grain elevator. The worst case scenario used to estimate the maximum acceleration was that the ALEXANDER HENRY (or similar displacement ship) impact the corner of the dock at a speed of 5 knots. With this scenario, the maximum acceleration felt in the grain elevator would be 1.5 m/sec^2 or 0.15 g.

Instrumentation

The transducer locations for tests 1 and 2 are shown in Figure 3.4. The five Hexpacks (a Hexpack is an ARCTEC CANADA designed ice pressure sensor), two averaging and three segmented, were used to measure ice pressure. They were installed by cutting a slot in the ice and freezing transducers in the positions shown. Two thermistor strings were also frozen into the ice. Each string contained three thermistors with the first thermistor approximately 0.15 m from the bottom, the second in the middle and the third approximately 0.15 m from the top of the ice. An accelerometer and video camera were used mounted at a height of approximately 35 m above the dock. The accelerometer's sensitive axis was carefully aligned to be perpendicular to the dock.

The data collection system used for these tests is shown in Figure 3.5. The fourteen Hexpack channels were conditioned with two series 2110 Vishay strain gauge conditioners. The accelerometer and Hexpack signals were recorded in parallel in both digital and analogue form.

The transducer locations for test 3 are shown in Figure 3.6. Apart from the relocation of the Hexpacks, the addition of another accelerometer on the UGGM elevator and the removal of one thermister string, the data collection system is identical.

FIGURE 3.4

TRANSDUCER LOCATION FOR TESTS 1 AND 2

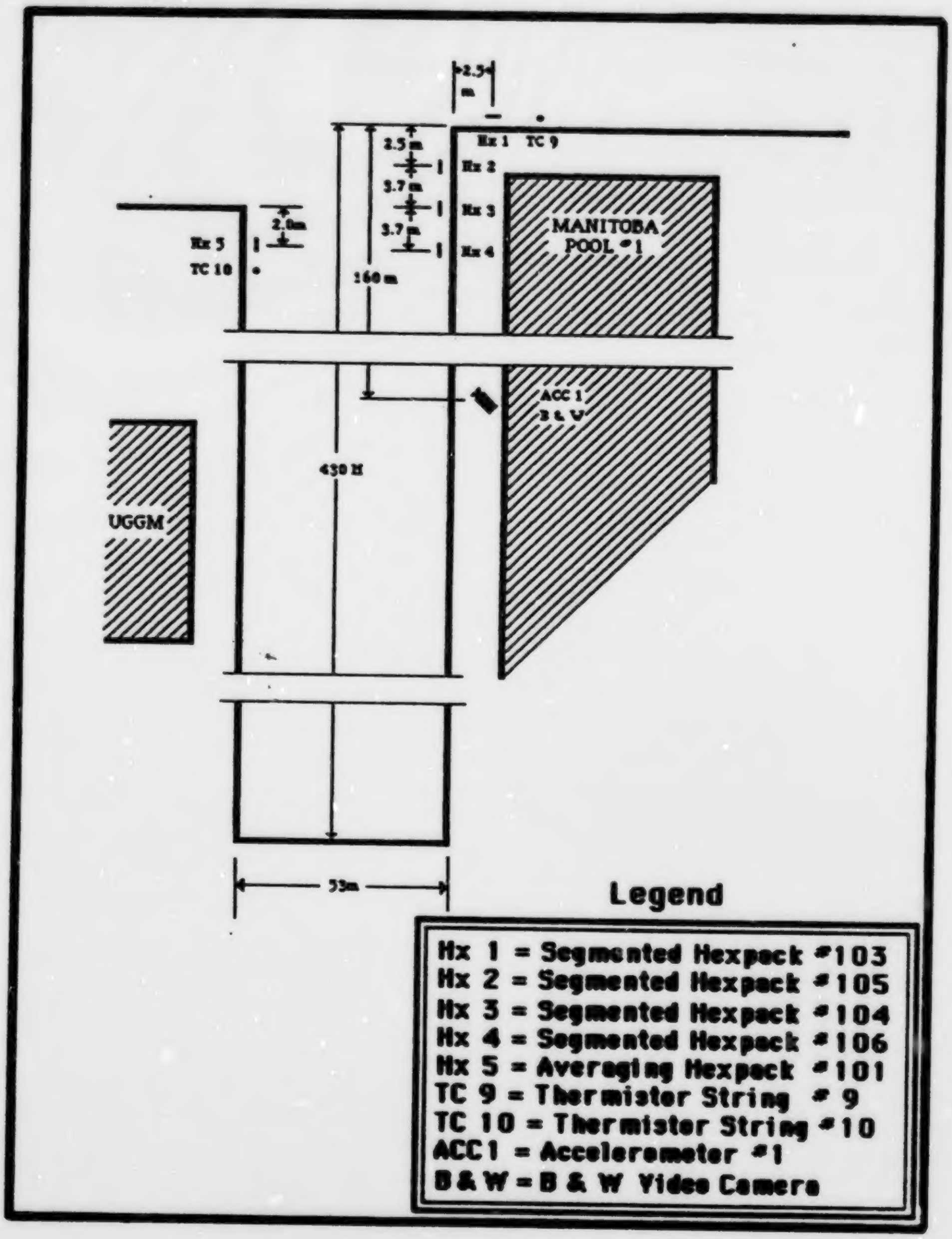

2.5 m
Hx 1
TC 9
2.5 m
Hx 2
3.7 m
Hx 3
3.7 m
Hx 4
2.0m
Hx 5
TC 10
160 m
MANITOBA POOL #1
ACC 1
B & W
430 M
UGGM
33m
Legend
Hx 1 = Segmented Hexpack #103
Hx 2 = Segmented Hexpack #105
Hx 3 = Segmented Hexpack #104
Hx 4 = Segmented Hexpack #106
Hx 5 = Averaging Hexpack #101
TC 9 = Thermistor String # 9
TC 10 = Thermistor String #10
ACC1 = Accelerometer #1
B & W = B & W Video Camera

FIGURE 3.5

DATA COLLECTION SYSTEM

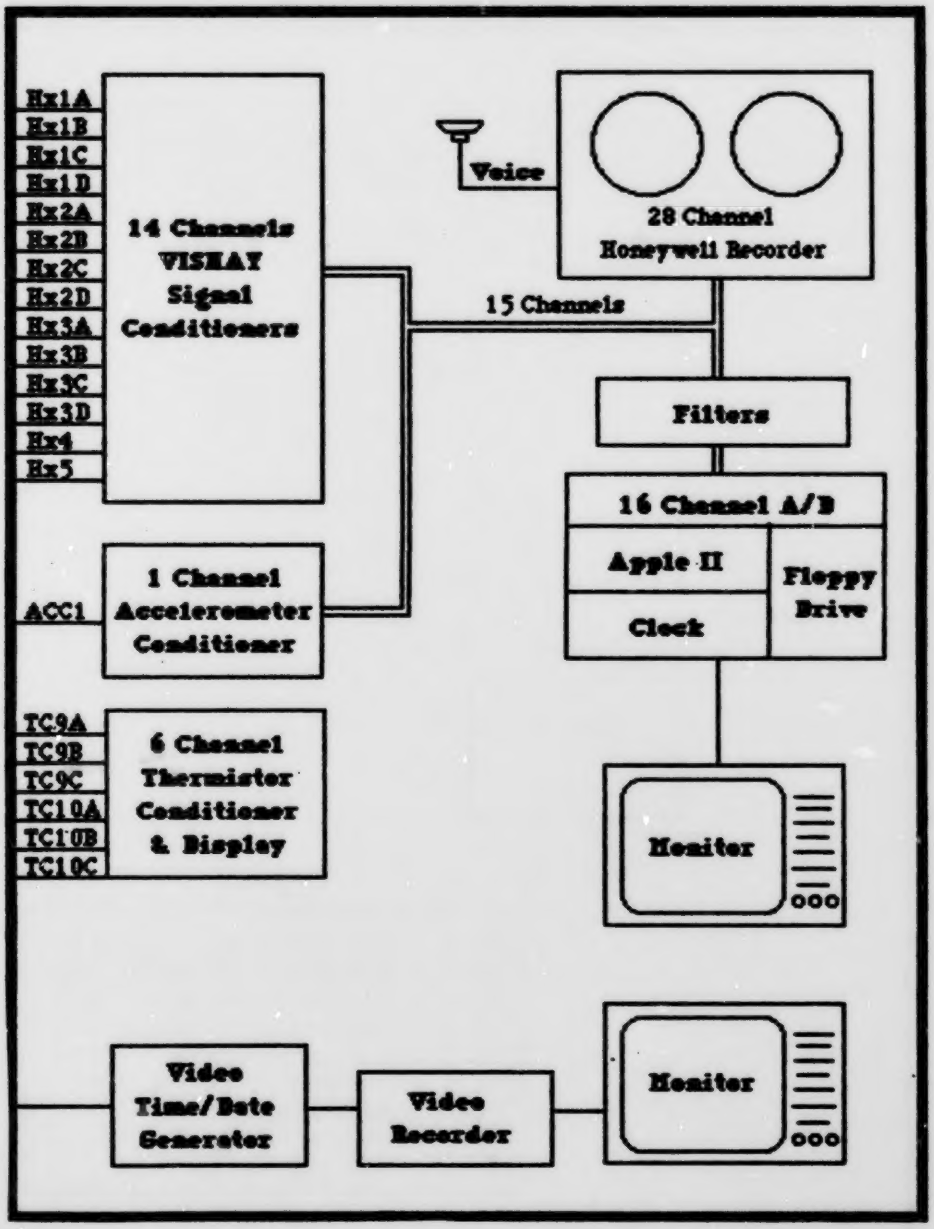
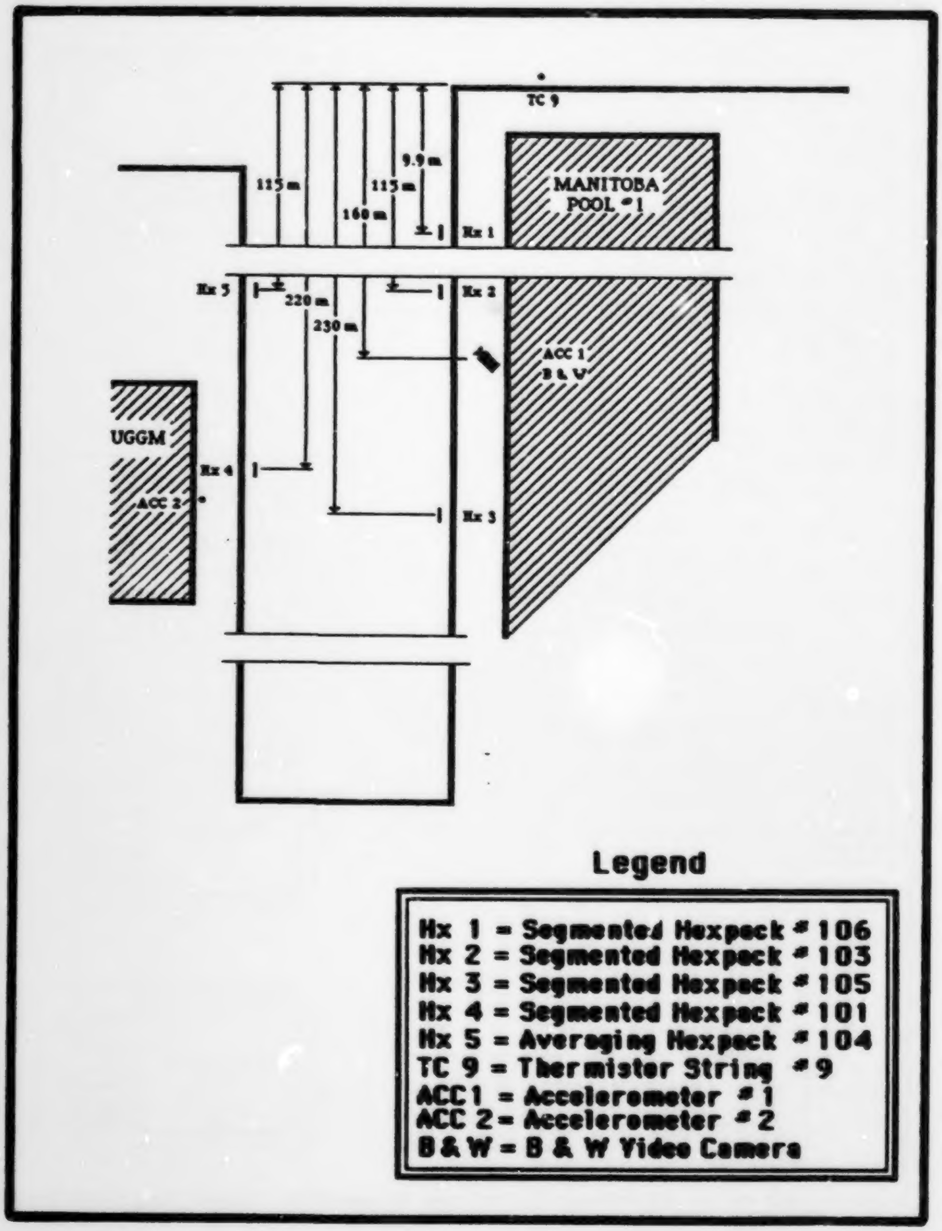

Hx1A
Hx1B
Hx1C
Hx1D
Hx2A
Hx2B
Hx2C
Hx2D
Hx3A
Hx3B
Hx3C
Hx3D
Hx4
Hx5
14 Channels VISHAY Signal Conditioners
Voice
28 Channel Honeywell Recorder
15 Channels
Filters
16 Channel A/D
Apple II
Clock
Floppy Drive
ACC1
1 Channel Accelerometer Conditioner
TC9A
TC9B
TC9C
TC10A
TC10B
TC10C
6 Channel Thermistor Conditioner & Display
Monitor
Video Time/Date Generator
Video Recorder
Monitor

FIGURE 3.6

TRANSDUCER LOCATION FOR TEST 3


TC 9
9.9 m
115 m
115 m
160 m
Hx 1
MANITOBA
POOL #1
Hx 5
220 m
230 m
Hx 2
ACC 1
B & W
UGGM
Hx 4
ACC 2
Hx 3

Legend

Hx 1 = Segmented Hexpack # 106
Hx 2 = Segmented Hexpack # 103
Hx 3 = Segmented Hexpack # 105
Hx 4 = Segmented Hexpack # 101
Hx 5 = Averaging Hexpack # 104
TC 9 = Thermister String # 9
ACC 1 = Accelerometer # 1
ACC 2 = Accelerometer # 2
B & W = B & W Video Camera

4. RESULTS

4.1 Air Cannon Bubbler Experiment

Evaluation Criteria

Measurements of water temperature and ice melting during the experiment allowed an evaluation of ice suppression using air bubblers according to several criteria. These included:

(1) Effect of bubbler on water temperature and circulation.

(2) Thermal reserve available for melting ice.

(3) Effect of deflectors on development of horizontal flow.

(4) Ice melting capability and efficiency.

Water Temperature

Figure 4.1 illustrates water temperatures and other environmental data during the tests. Wind, sunshine and air temperature are from Thunder Bay Airport, while water temperatures are from array #2 at the test site.

At this site the bubbler clearly affected a complete vertical mixing of the water column within a period of one day. A similar pattern was observed at all bubbler sites and was not observed at array #1 (Figure 4.2). Overall mean water temperature at all sites dropped from 1.12°C to 1.07°C during the first day of bubbling and rose to 1.33°C by the end of the test.

Thermal Reserve Available for Melting Ice

The availability of heat energy measured in the slip is compared with energy requirement to melt the ice cover and with energy actually used (Figure 4.3). The thermal reserve prior to bubbling in 1984 was sufficient to melt about 17% of the total ice cover in the slip, assuming ice at 0°C and no heat loss to the air. This compares with about 10% in 1983 [7]. Figure 4.3 clearly shows that energy was added to the slip to affect the observed melting. Possible sources of energy included warm water in the harbour, a surface water discharge from the Saskatchewan Pool elevator or solar heating.

Effect of Deflectors on Development of Horizontal Flow

Theoretical considerations and laboratory tests indicated that air cannon bubblers with deflectors develop more horizontal flow than do conventional bubblers or air cannons without deflectors. Horizontal flow development was illustrated during the experiment in two ways.

First, thinning of the ice two meters from the edge of the bubbler holes was observed. Repeated measurements of the radius of thinning were not possible for safety reasons, but the visual observations suggest that horizontal flow did occur.

FIGURE 4.1

TEST ENVIRONMENTAL DATA

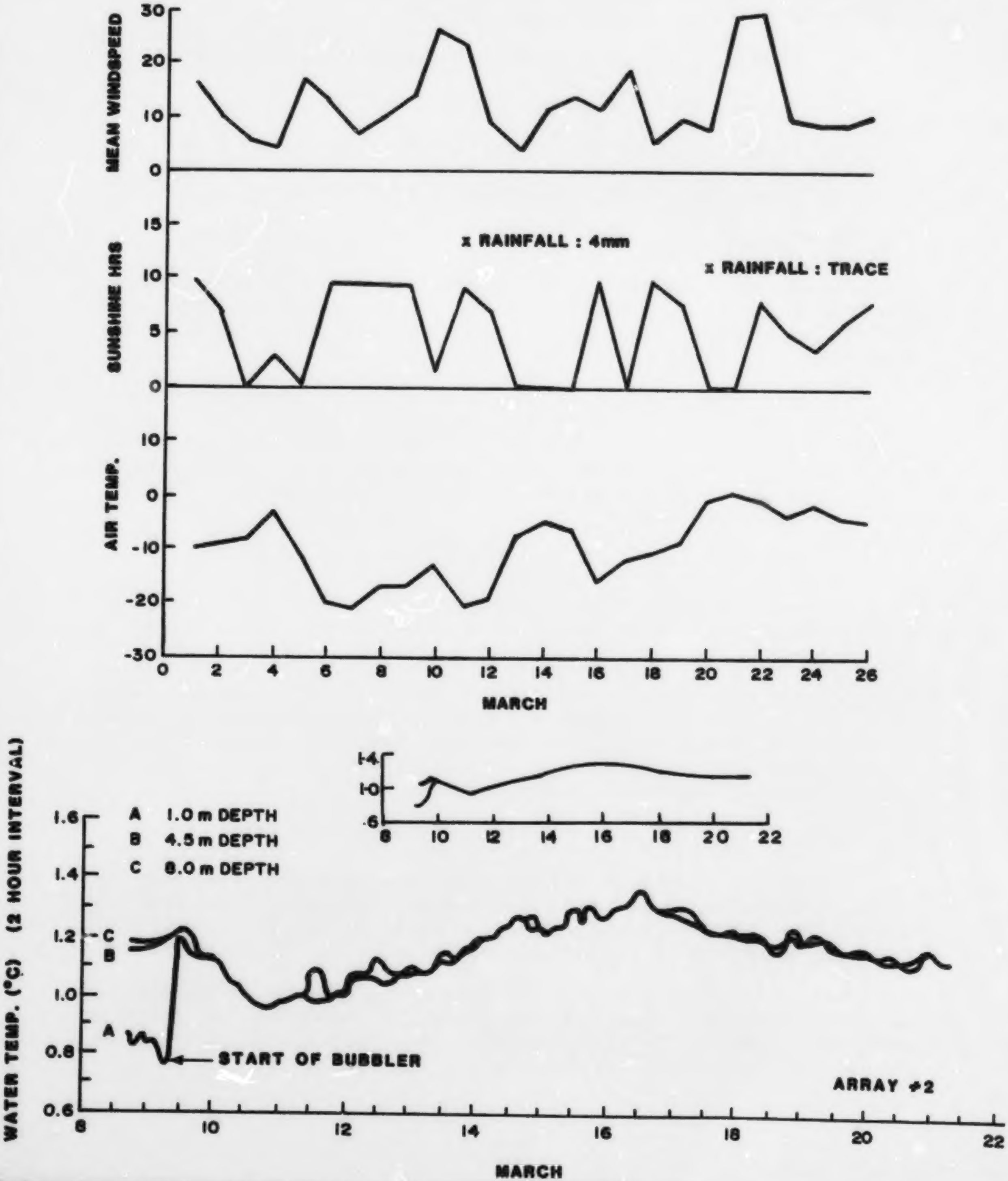
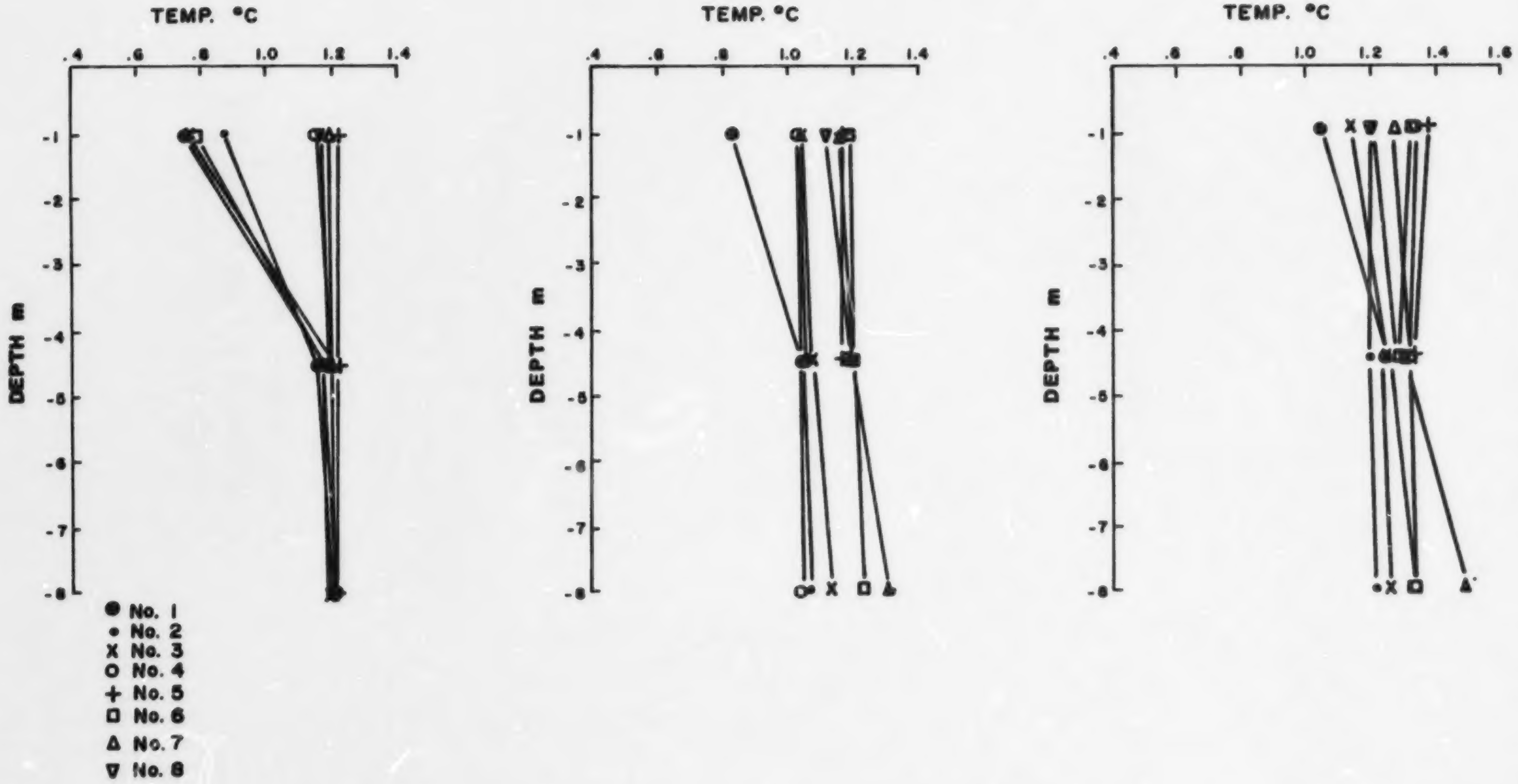


FIGURE 4.2

WATER TEMPERATURE PROFILES for CANADA MALTING SLIP



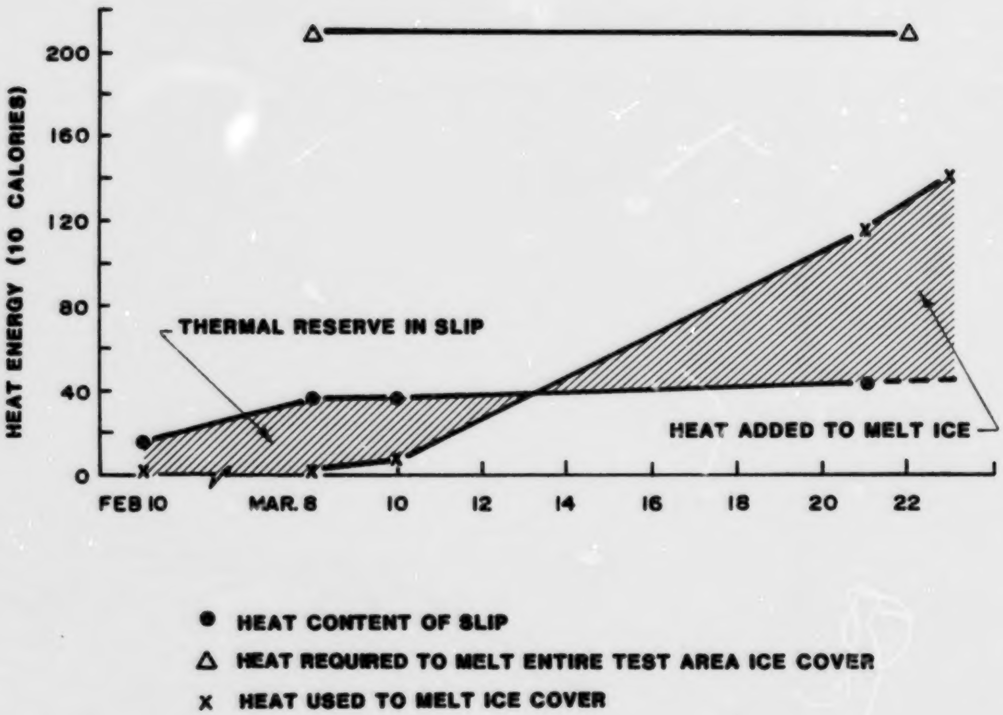
4.2a MARCH 8, 1984 6:00 PM

4.2b MARCH 10, 1984 6:00 AM

4.2c MARCH 21, 1984 6:00PM

FIGURE 4.3

HEAT CONTENT in SLIP



Second, increased water temperatures were noted 48 m from the nearest bubbler, and this could result from horizontal circulation induced by the bubbler.

Direct comparisons of the effect of deflector types on flow development could not be made since the deflector orientation was not constant during the experiment.

Ice Melting Rate and Efficiency

The overall rate of ice melting was determined by measuring the change in open water areas on air photographs.

Measurements in the slip and the harbour indicated no natural thinning of the ice cover during the test period and therefore, ice thickness was assumed constant at 65 cm for purposes of calculating melting rates. This results in conservative estimates of ice melting, since field and laboratory [11] observations indicate that the air cannon bubblers do melt the underside of the ice cover.

Figure 4.4 compares the cumulative area melted by each of the air cannon, "rake" diffuser and point source bubbler systems. The cannon system clearly melted the largest area of ice overall and showed the highest rate of melting through most of the test period, with an overall average rate of 193 m^2/day.

The "rake" diffuser system was operated for a longer time period (started bubbling March 1st) and melted less ice. The average melting rate for this system was less than 82 m^2/day, and the point source bubbler melted 17.8 m^2 of ice per day, after bubbler holes became visible in the air photographs.

The air cannon system used an air supply rate of 0.132 m^3/s at 76 kPa, while the "rake" diffuser system used a rate of 0.040 m^3/s at pressure of 690 kPa. The air cannon thus melted 0.017 m^2 of ice per m^3 of air to the rake diffuser's 0.23 m^2 per m^3. The efficiency of the air cannon system is higher however, because less energy is used to supply air at lower pressure. The air cannon system used a 20 HP blower while the rake diffuser used a 40 HP compressor. Air supply to the point source bubblers was not measured.

Cost Comparison

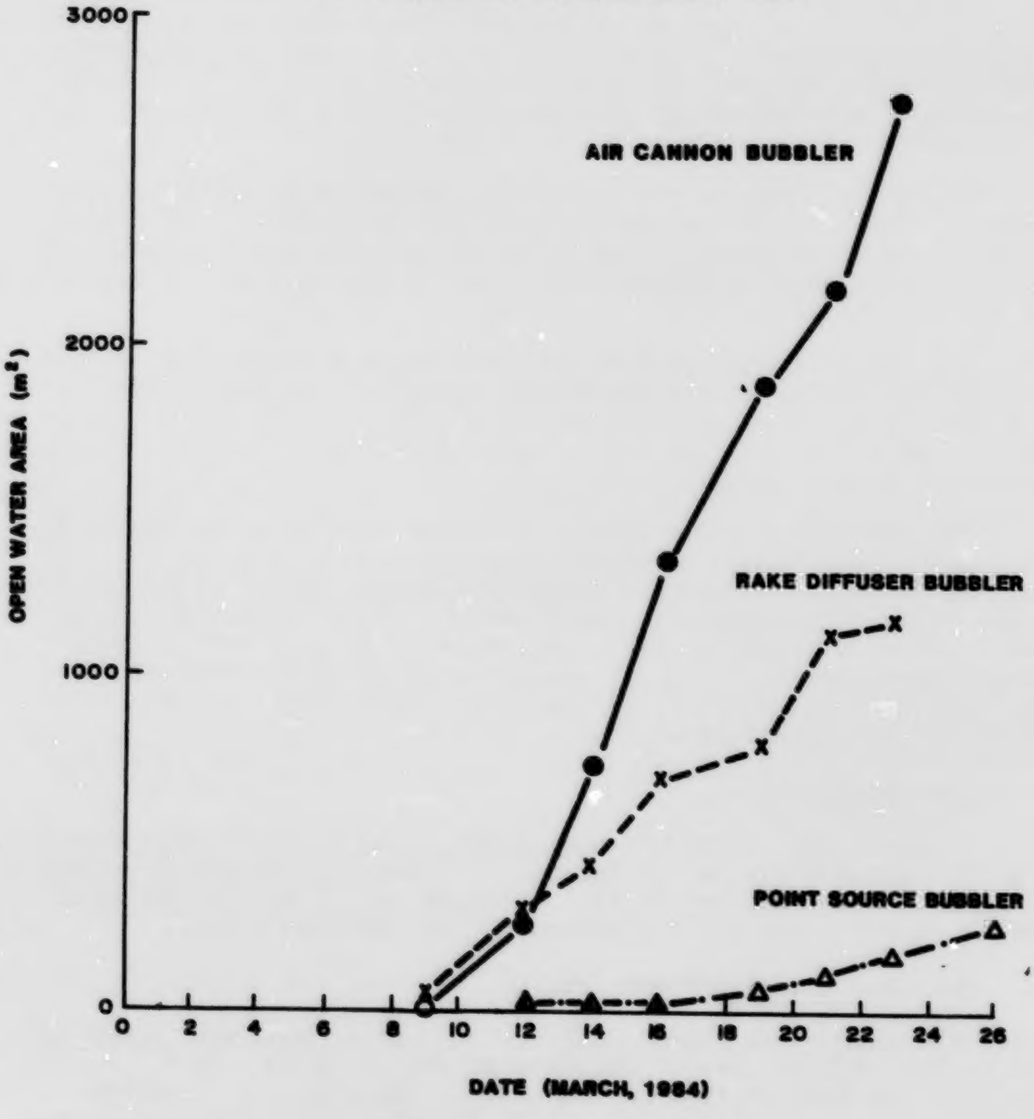
A comparison of capital, deployment, operating and maintenance costs showed that the rake system cost less than the air cannon system on a one year cost recovery basis. Amortized over 5 years of operation, the air cannon system was more economical, per unit ice melted.

4.2 Dock Load Experiment Results

The entire ice force analysis has been performed using an arbitrarily defined zero. Since thermal changes cause a considerable ice load, an absolute zero was not known. Therefore, the measurements obtained are ice loads with respect to the arbitrarily selected zero.

FIGURE 4.4

AREA MELTED by THREE DE-ICING SYSTEMS
AT THUNDER BAY, MARCH 1984



For all three tests, the arbitrarily selected zero was taken approximately five to ten minutes before the test started with the ALEXANDER HENRY well clear of the ice. Since the absolute zero was not known, all tests were scheduled to occur as early as possible in the morning when thermal ice loads would be lower [13].

Table 4.1 summarizes the results of all tests with Figures 4.5 to 4.10 showing a schematic representation of the dock loads. Superimposed on these figures is the approximate position of the ship as well as the broken ice channel. Shown as a dotted line is the expected maximum dock load derived by interpolating and extrapolating from these measured results.

During test 1, the ice forces measured by all five Hexpacks varied widely. Hexpack 1, which is located on the end of the dock, never exceeded a load of 15 kN/m during icebreaking beyond the slip; however, during this same time, the Hexpacks in the slip reached a considerable load. Hexpacks 2, 3 and 4, which are within a span of 7.4 m, varied significantly. With the exception of runs 2 and 8, the further the measurement was taken away from the end of the dock the higher the load recorded was. This was to be expected since the lengths of the Manitoba Pool #1 and UGGM piers are not equal. As a pressure is produced in the intact ice sheet, (either by thermal effects or by a ship) the ice loads closer to the end of the Manitoba Pool dock would not be as constrained as the loads farther along. This was because the rigidity of the opposing dock was considerably higher than the rigidity of the unconstrained ice, outside the dock. It was expected that by placing the three Hexpacks in this manner, the measured peak force would be on either Hexpack 2 or 3 and that the load measured by Hexpack 4 would have been lower. However, it appears that the peak force occurs past Hexpack 4. Therefore, the value of the peak force is not known. Due to a stress concentration near Hexpack 5, it is expected that the peak force seen on the Manitoba Pool #1 side would be lower than the value measured by Hexpack 5.

Although the location of Hexpack 5 is opposite to Hexpack 4, the ice load measurements are considerably higher. On average, the ice loads measured with Hexpack 5 are 2.6 times larger than Hexpack 4. The reason for this is the unequal lengths of the two docks. As discussed above, the ice loads closer to the end on the Manitoba Pool slip are not as constrained as the loads farther along the dock. However, these ice loads must have a reaction if the ice is to remain stationary. Consequently the ice load measured by Hexpack 5 is larger due to a smaller reaction area. Figures 4.5 and 4.6 show a schematic representation of the ice loading parallel to the dock face caused by pressure applied by the icebreaker in the harbour. With the exception of a small amount of shear reaction across the end of the UGGM dock, the areas under the load distribution curves must be equal. Therefore, the loads measured at the end of the UGGM dock must be considerably larger than the loads measured along the same length of the Manitoba Pool #1 dock.

In general, as the ALEXANDER HENRY got closer to the dock the ice loads increased. The highest ice load measured during test 1 occurred on the UGGM side and measured 183.5 kN/m. The highest measurement of the Manitoba Pool #1 side occurred at approximately the same time on

TABLE 4.1

ICE LOAD RESULTS

TEST NO.	RUN NO.	MAXIMUM ICE PRESSURE					SHIP POSITION
		HEXPACK #1 (kN/m)	HEXPACK #2 (kN/m)	HEXPACK #3 (kN/m)	HEXPACK #4 (kN/m)	HEXPACK #5 (kN/m)	
1	1	12.03	5.89	18.40	27.23	96.18	120 m E-S-E of dock
1	2	7.92	4.87	15.06	6.20	23.60	beyond range
1	3	14.82	17.16	30.54	42.13	126.66	120 m E-S-E of dock
1	4	8.54	9.05	23.44	44.45	68.32	80 m E-S-E of dock
1	5	5.62	8.22	11.84	56.21	119.66	15 m East of dock
1	6	BF[*1]	37.55	40.67	65.15	NF[*2]	75 m East of dock
1	7	BF	36.54	38.64	72.27	131.53	60 m East of dock
1	8	BF	22.04	12.35	74.76	183.49	45 m East of dock
2	1	BF	65.00[*3]	125.00[*3]	25.49	NF	0 to 20 m inside dock
2	2	BF	BF	50.00[*3]	41.55	NF	Stopped 20 m inside dock
3[*4]	1	NF	25.81	52.21	23.85	121.73	20 to 45 m inside dock
3	2	42.58	24.52	36.13	23.10	141.85	45 to 70 m inside dock
3	3	BF	8.99	85.10	30.60	113.11	100 to 145 m inside dock
3	4	BF	BF	178.09	121.78	3.95	205 to 230 m inside dock

[*1] BF indicates that the Hexpack was broken free of the ice.

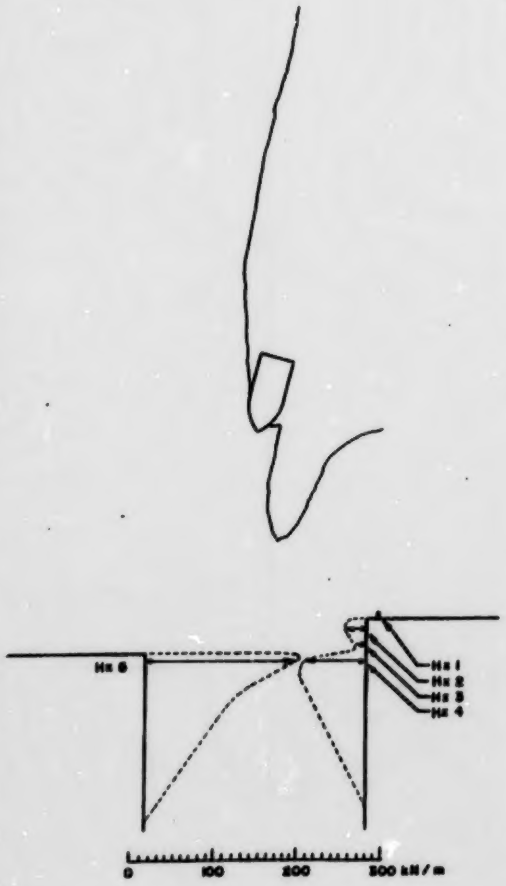
[*2] NF indicates that the Hexpack is not functioning correctly due to either a stress concentration in the ice, or being disconnected.

[*3] These loads are estimates.

[*4] Test # 3 used a different location for the Hexpack.

FIGURE 4.5

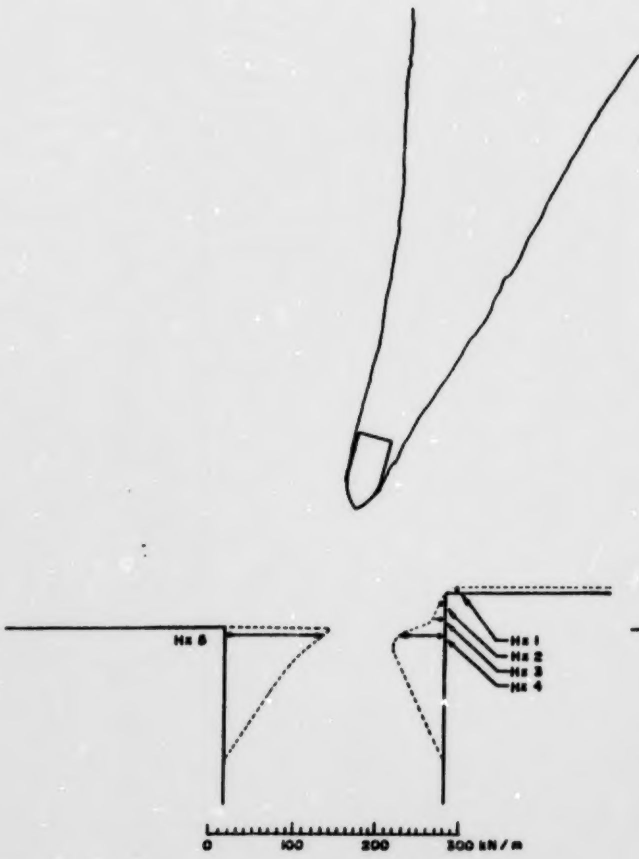
DOCK LOAD DISTRIBUTION
TEST 1 RUN 08



Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN/m

FIGURE 4.6

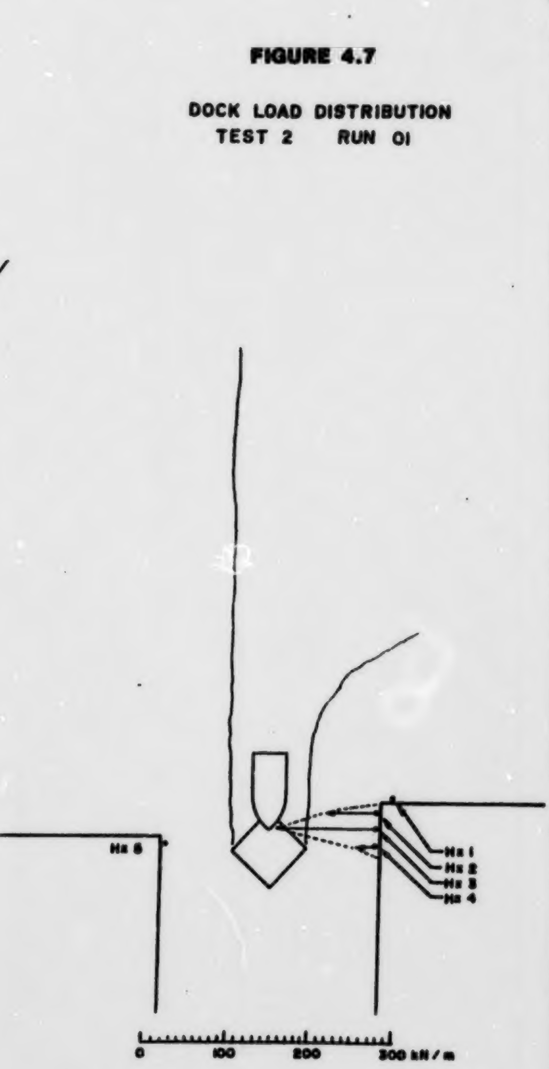
DOCK LOAD DISTRIBUTION
TEST 1 RUN 05



Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN/m

FIGURE 4.7

DOCK LOAD DISTRIBUTION
TEST 2 RUN 01



Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN/m

FIGURE 4.8

DOCK LOAD DISTRIBUTION
TEST 3 RUN 02

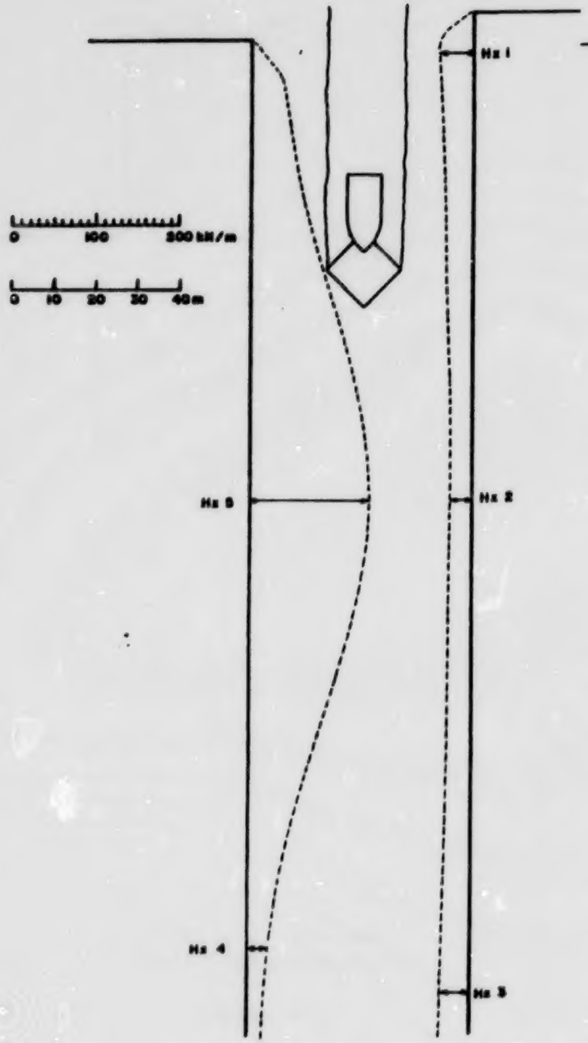

0
100
200 kN/m
0
10
20
30
40m
Hx 1
Hx 2
Hx 3
Hx 4
Hx 5

FIGURE 4.9

DOCK LOAD DISTRIBUTION
TEST 3 RUN 03

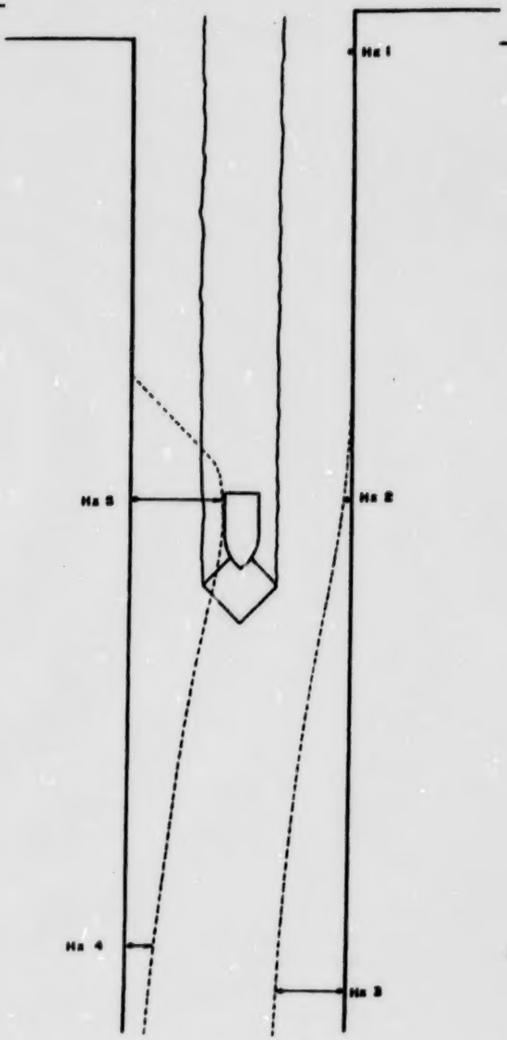
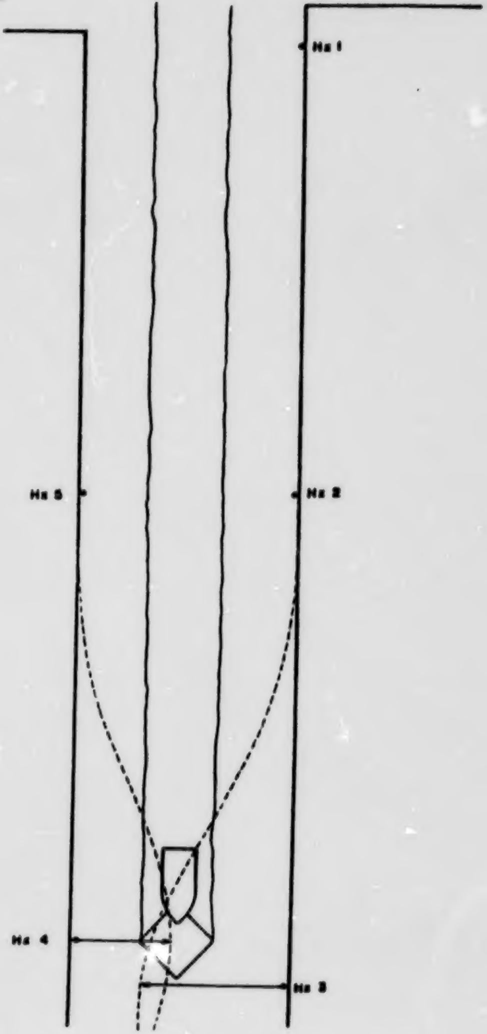

Hx 1
Hx 2
Hx 3
Hx 4
Hx 5

FIGURE 4.10

DOCK LOAD DISTRIBUTION
TEST 3 RUN 04


Hx 1
Hx 2
Hx 3
Hx 4
Hx 5

Hexpack 4 and measured 74.8 kN/m. Since the ALEXANDER HENRY was not permitted to enter the slip during test 1, these ice forces would be equivalent to what the dock would regularly see while the harbour is being opened each year.

Figure 4.7 shows a typical example of measured dock loads while the ALEXANDER HENRY notched to the ACIB was brought into the slip. During test 2, run 1, the ALEXANDER HENRY started at the edge of the unbroken ice and penetrated approximately 20 meters inside the dock. During this period Hexpacks 2, 3 and 4 measured maximum loads of 65.0, 125.0 and 25.5 kN/m respectively. Contrary to what was observed during test 1, the ice pressure distribution changed so that the peak force was measured with Hexpack 3.

Test 2, run 2, occurred while the ACIB was hovering after completion of the previous ram. During this interval the measured dock loads were lower than during the ram. An interesting observation noted during both tests with the ACIB was that on occasion a periodic oscillation was recorded by the Hexpacks. This frequency of oscillation coincides with the 1 Hz frequency of the ACIB cushion pressure as reported in [12].

Figures 4.8, 4.9 and 4.10 summarize the ice loads measured during test 3. Run 1 occurs while the ACIB is passing Hexpack 1. Runs 2 and 3 occur while the ACIB is approaching and passing Hexpacks 2 and 5, while run 4 occurs while the ACIB is passing Hexpacks 3 and 4.

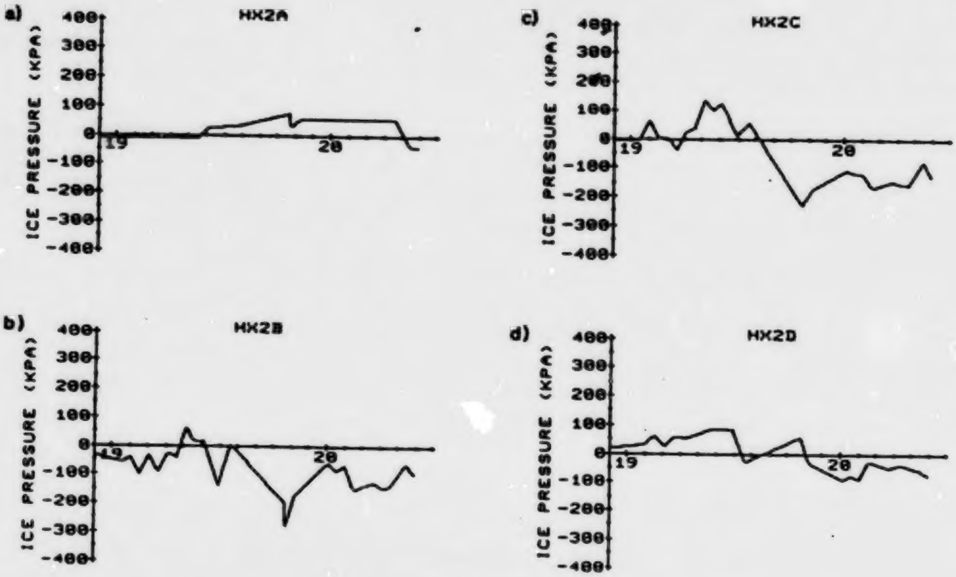
The three highest loads measured during test 3 are 178.1, 143.9 and 121.8 kN/m. The first and last values were measured on Hexpack 3 and 4 respectively as the ACIB passed the workhouse (the point approximately midway along the slip). The second value was measured on Hexpack 5 as the ACIB approached the workhouse. Throughout the entire series of tests, the maximum acceleration recorded was 0.01 g.

Thermal Loads

During a 36 hour period, between March 18 and March 20, the ice pressures due to thermal stresses were measured. During this same time both air and ice temperatures were recorded. The temperature at the top of the ice ranged between -3.9°C and -0.1°C, while the temperatures near the bottom ranged between -1.7°C and -0.2°C. This temperature fluctuation as well as temperature differential produce thermal stresses which were recorded by the Hexpacks. As reported by Bomeng [13], the thermal ice pressure is greatest in the top 30 cm of the ice and gradually diminishes with depth. This agrees with the measurements recorded by the Hexpacks. Figure 4.11 shows the time series plots of Hexpack 2 beginning at 2200 hours on March 18 and ending at 1200 hours on March 20. Segment A is virtually out of the ice and as such records little pressure. However, segments B (being in the top third of the ice), C (being in the middle) and D (being in the bottom) record progressively lower pressures. The maximum pressure fluctuation due to thermal effects is recorded by segment B, varying between +50 kPa to -275 kPa. This ice pressure translates to a dock load ranging between +100 kN/m to -300 kN/m during a relatively mild variation of air temperature.

FIGURE 4.11

ICE PRESSURE VARIATION
DUE TO THERMAL CHANGE



5. CONCLUSIONS

5.1 Air Cannon Bubblers

The air cannon bubblers were highly effective at mixing a stratified water column. Initially stratified water columns were completely mixed by the air cannons within one day of operation, and horizontal flow developed by the bubblers created a circulation of surface water at least 48 m from the nearest bubbler.

The heat available in the slip was theoretically sufficient to melt only 17% of the ice cover. Measurements showed that a much larger volume of ice was melted than could be explained by the thermal reserve available in the slip and in addition, the available thermal reserve increased during the test period. This leads to two important conclusions. First, heat was added to elevate the slip temperature from some natural source prior to ice breakup. Second, the capability of ice suppression at Thunder Bay was not limited by the initial thermal reserve in the elevator slip.

In terms of overall ice melting, the air cannon system melted ice at a mean rate of 193 m^2/day. This was more than twice as fast as a rake bubbler system operating in the same elevator slip. The air cannon system also melted the ice cover at a more constant rate than did the rake system.

The air cannon system was also more efficient than the rake system. First, the low pressure blower which was used to supply air to the air cannons, consumed less power (20 HP) than the high pressure compressors (40 HP) required to supply air to the rake system. Second, the air cannon system required less frequent in-service maintenance than did the rake system.

Finally, the air cannon system was more economical than other systems when costs were amortized over a 5 year operating life.

5.2 Dock Loads

(1) The maximum allowable force along the full length of the dock was calculated to be 365 kN/m.

(2) The maximum force measured due to thermal expansion of the ice was between 300 and - 100 kN/m.

(3) The peak force measured when the ALEXANDER HENRY icebreaker approached the entrance of the slip reached a maximum force of 184 kN/m (run 1). The force was considered too high and no further tests were carried out with the ALEXANDER HENRY.

(4) The peak force measured when the ALEXANDER HENRY coupled with the Air Cushion Icebreaking Bow (ACIB) penetrated about 25 m into the slip (run 2) is 125 kN/m. The ice was not broken by the ACIB but by the icebreaker's bow. The test was stopped.

(5) The peak force measured during the penetration of the ALEXANDER HENRY coupled with the ACIB (run 3) into the slip was 178 kN/m.

(6) The forces applied on the dock wall as a result of the penetration of a vessel were found to be significant. The forces attainable may exceed the design maximum load if a preloading caused by thermal stresses exists. The latter are at maximum when the temperature of the ice increases significantly in a short period of time.

(7) The pressure applied on structures located around navigation channels may be successfully evaluated using experimental and analytical techniques. The use of a conventional icebreaker to break up an intact ice cover inside the slips at Thunder Bay must not be permitted. The Air Cushion Icebreaking Bow has proven to be an efficient and safer bow to use in the slips. Other vessels with advanced bows that break ice with a downward force may also be used safely.

6. RECOMMENDATIONS

6.1 Air Cannon Bubblers

(1) Air cannon bubblers should be used to melt the ice cover in elevator slips at Thunder Bay Harbour.

(2) An additional study should investigate alternative bubbler designs or deployment systems which would allow easier deployment and removal of the cannon bubblers.

(3) The study to compare the effect of different deflector types on horizontal flow development should be repeated.

(4) Costs of air cannon bubblers, rake and conventional bubblers should be compared under a standard set of operating conditions and ice suppression requirements.

(5) A long term study should be undertaken to assess the slip-to-slip and the year-to-year variability in heat content of the slip, to assess potential for ice melting.

6.2 Dock Loads

(1) The use of a conventional icebreaker to break-up an intact ice cover inside the slips at Thunder Bay must not be permitted.

(2) The Air Cushion Icebreaking Bow has proven to be an efficient and safe bow to use in the slips. Other vessels with advanced bows that break ice with a downward force may also be used safely.

(3) The pressure applied on structures located around navigation channels should be evaluated using experimental and analytical solutions. Field experiments can be carried out by deploying a number of pressure transducers in ice and measuring the forces associated with the passage of a vessel nearby.

(4) Field experiments are expensive and should be complemented by laboratory experiments to evaluate the effect of the following variables:

- ice thickness
- ice properties
- vessel distance from structure
- structure stiffness
- structure shape
- vessel entering velocity
- bow shape
- thermal stress.

(5) The results of these laboratory experiments should be compared to the limited results obtained from the field experiments including the present study and compared as well to the finite element model results. Such a study should provide a complete understanding of the associated forces applied on structures surrounding the navigation channel due to ship traffic.

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TP 5834E

ICE MANAGEMENT IN THUNDER BAY HARBOUR
WINTER 1984
VOLUME 1 - CANNON BUBBLER EXPERIMENTS

PREPARED FOR:

TRANSPORTATION DEVELOPMENT CENTRE,
MONTREAL, QUEBEC.

JULY 1984

BY

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17. Abstract

Field experiments undertaken in March 1984 to evaluate the effectiveness of an air cannon bubbler system for clearing ice from an elevator slip are described The bubbler system was installed at Thunder Bay Harbour and consisted of ten air cannon bubblers which were operated for a period of two weeks.

Field measurements and observations during the two week period included air temperature, water temperature, ice thickness and ice cover area, and ice melting mechanisms.

The cannon bubbler system is compared with two other bubbler systems used at Thunder Bay in 1984. The study concludes that the air cannon bubbler system was both faster and more efficient than a rake bubbler system in melting the ice cover in the slip, and was faster than a point source bubbler in an adjacent slip. The system mixed water in the slip within about 50 metres of the air cannons and melted about 2750 m^2 of ice cover in 12 days. This is more ice melting than can be explained by the thermal reserve of water in the slip. A cost analysis concluded that, over a 5-year amortization period, the 10-unit air cannon system would be more economical than the rake system and point source bubbler system.

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17. Résumé

Ce rapport rend compte des expérimentations conduites dans le port de Thunder Bay, en mars 1984, et visant à évaluer l'efficacité d'un système de déglaçage mettant en oeuvre des mélangeurs à canon pneumatique. Installé au fond d'un bassin de chargement céréalier, ce système comptait 10 mélangeurs qui ont été utilisés deux semaines durant.

Les mesures et observations faites au cours de cette période ont concerné la température ambiante et celle de l'eau, l'épaisseur de la glace, la superficie déglacée, ainsi que les mécanismes de la fonte.

Les résultats obtenus sont comparés à ceux de deux autres systèmes essayés dans le même port en 1984. Le système à canons pneumatiques serait plus rapide et plus efficace que le système à diffuseurs d'air en configuration "râteau" et plus rapide qu'un diffuseur d'air linéaire essayé dans un bassin adjacent. Son rayon d'action comme mélangeur a été de 50 mètres et, en 12 jours, il a réussi à fondre 2 750 m^2 de glace, ce qui est plus que le seul potentiel thermique de l'eau du bassin permettait d'espérer. Enfin, une analyse de coûts a montré que sur une période d'amortissement de 5 ans, ce système serait plus économique que les deux autres.

18. Mots-clés: Maîtrise des glaces, déglaçage, ports, quais, bassins portuaires, véhicule à coussin d'air, proue, essais

19. Diffusion: Le CDT dispose d'un nombre limité d'exemplaires.

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22. Nombre de pages: 66
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1. INTRODUCTION

1. INTRODUCTION

1.1 Background

Ice management systems have long been used by engineers to clear ice in waterways and harbours in most parts of the northern world.

A significant effort has been made by Transport Canada during recent years to investigate means of clearing ice-covered harbours. Several studies were carried out at Thunder Bay Harbour, the most northern harbour on the St. Lawrence Seaway. These projects included: the development of an air cushion icebreaking bow (ACIB), the installation of bubbler systems in two slips (Hill [1] and Kamo et al [2,3]), the installation of an air cannon bubbler developed by Atara Corporation [4] the measurement of water temperatures in various slips [5], the review of various ice management alternatives [6] and ice management techniques evaluation [7].

Other solutions are provided by experience in the Scandinavian countries with flow developers and wave making equipment. Eranti [8,9] reports ice control studies with flow developers and bubblers in Finnish harbours and the Saimaa Canal. Andersen [9] describes clearing of ice from a harbour in Denmark with man-made waves.

1.2 Previous Experiments at Thunder Bay Harbour

Earlier work with bubblers at Thunder Bay indicated two shortcomings [2,3]. First, the area melted was limited, and melting of an area large enough to accommodate a ship would require an extensive system of bubblers. Second, the system was heavily damaged by ship operations during the open water season.

A portable "rake" system [3] was developed which allowed some control over the geographical area melted, and also could be removed prior to the shipping season. During tests in 1983 the system did not melt the volume of ice expected.

An alternative, "air cannon bubbler" type system [4,5,10] was also tested. This system was designed to generate a higher velocity current which is potentially more successful at producing a warm water convection and melting the ice cover. Measurements during that program however, raised questions as to the thermal reserve available for melting ice at Thunder Bay and the effectiveness of the induced flow in developing horizontal currents.

2. OBJECTIVES

The overall objective of this program was to achieve a guaranteed opening of Thunder Bay Harbour by the 1st of April every year.

This experimental program had two objectives. One was to evaluate the effectiveness of a series of air cannon bubblers with deflectors installed, in developing horizontal flow capable of melting the ice cover in one of the Thunder Bay Harbour slips. The second was to compare the results with other systems deployed in the same area.

3. WINTER 1984 TEST PROGRAM

3.1 Site Description

3.1.1 Location

The bubbler tests were conducted at the Port of Thunder Bay, Ontario, located on Lake Superior at latitude 48°N and longitude 89°W. Thunder Bay is at the western end of the Great Lakes waterway system and is 3200 km from the Atlantic Ocean.

Figure 3.1 illustrates details of Thunder Bay Harbour and various slips where bubbling and other ice suppression tests have been undertaken by Transport Canada and Lakehead Harbour Commission. Air cannon bubbler tests were conducted at the Canada Malting slip in March, 1984 and at the Saskatchewan Pool #7A/United Grain Growers slip in 1983.

Details of the test site are shown in Figure 3.2. The Canada Malting/Saskatchewan Pool #7B slip is 350 m long, 50 m wide and 8-9 m deep. Tests were conducted on the Canada Malting side of the slip, in an area about 160 m x 25 m.

3.1.2 Environmental Conditions

Long-term and winter 1983-84 climatic data for Thunder Bay are presented in Table 3.1. Thunder Bay is in the South Laurentian climatic region where sub-freezing temperatures typically occur for seven months of the year, and approximately 40% of precipitation falls in winter. Temperatures at Thunder Bay are moderated by the influence of Lake Superior with freezing temperatures occuring on average for five months. Normal maximum ice thickness in Thunder Bay Harbour is 76 cm, occuring in late March.

FIGURE 3.1

THUNDER BAY HARBOUR

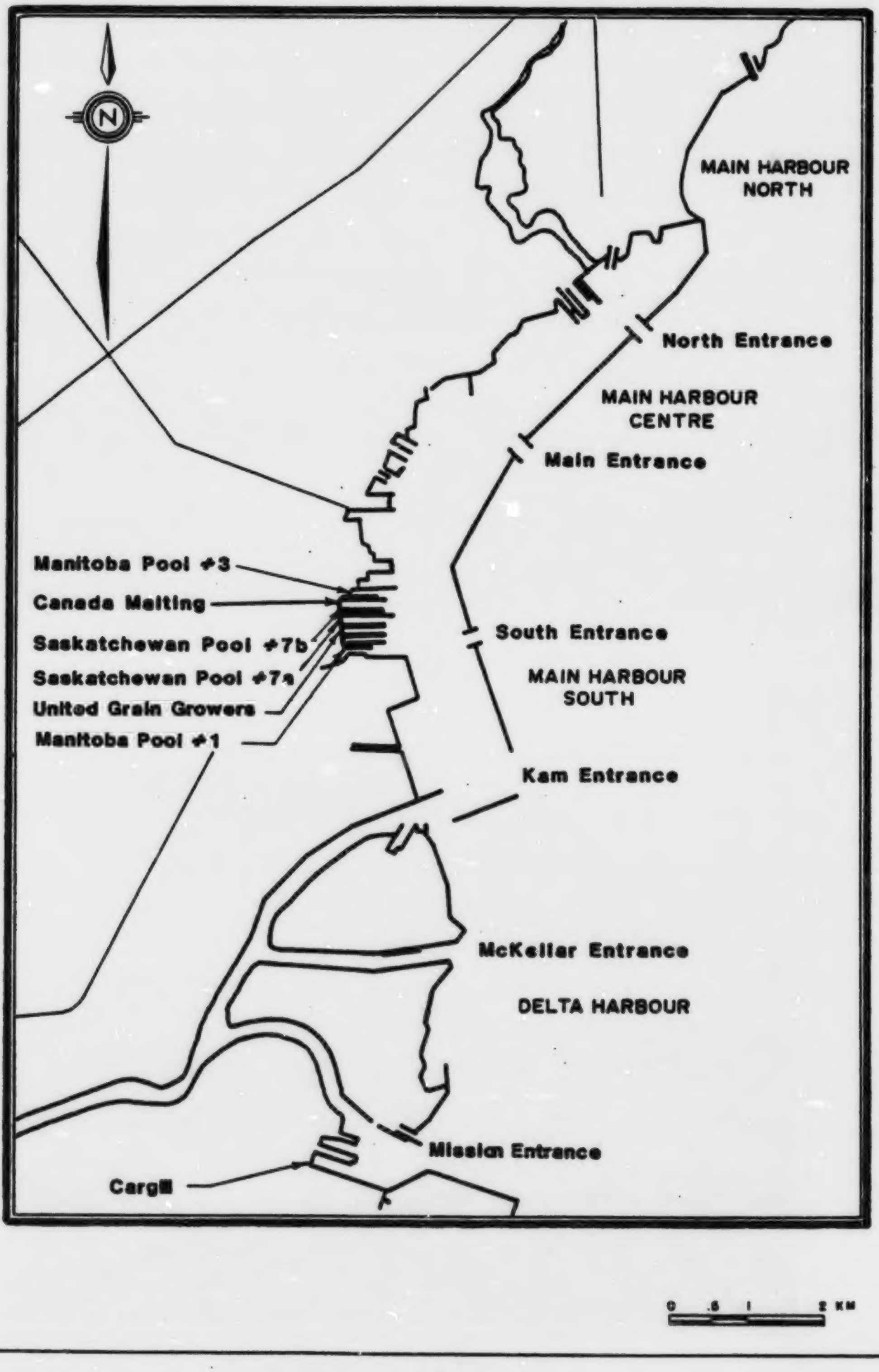
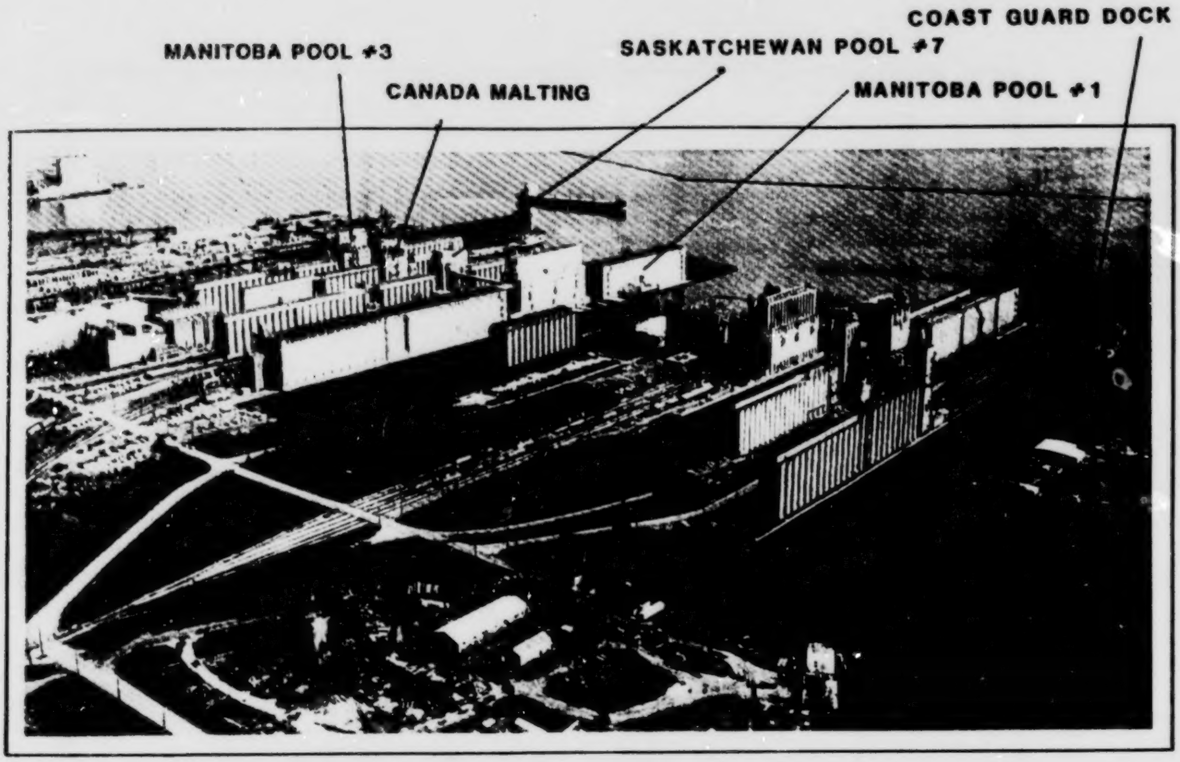
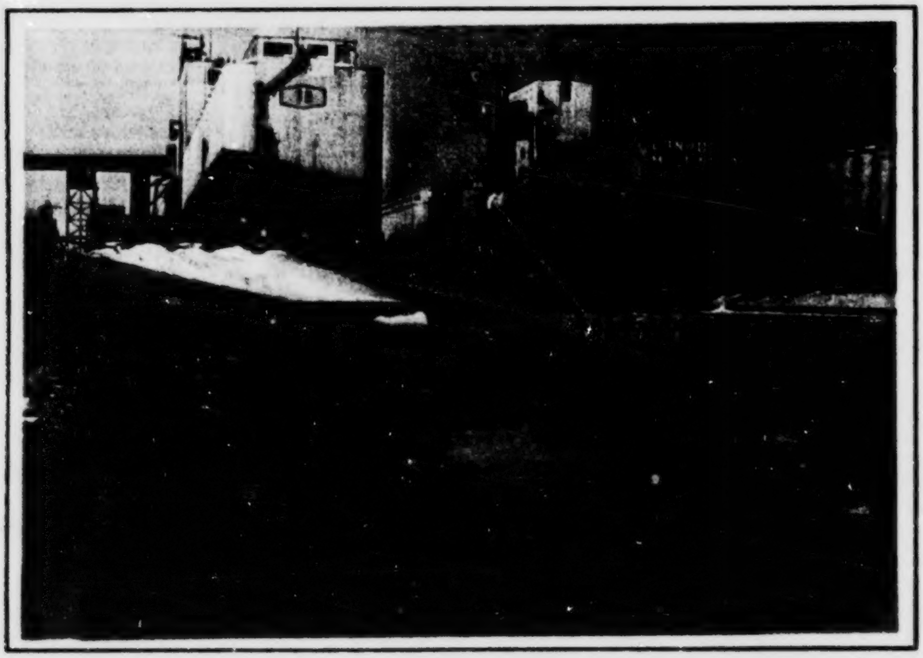

N
MAIN HARBOUR NORTH
North Entrance
MAIN HARBOUR CENTRE
Main Entrance
Manitoba Pool #3
Canada Malting
Saskatchewan Pool #7b
South Entrance
Saskatchewan Pool #7a
MAIN HARBOUR SOUTH
United Grain Growers
Manitoba Pool #1
Kam Entrance
McKellar Entrance
DELTA HARBOUR
Mission Entrance
Cargill
0 .5 1 2 KM

FIGURE 3.2
TEST SITE


COAST GUARD DOCK
MANITOBA POOL #3
SASKATCHEWAN POOL #7
CANADA MALTING
MANITOBA POOL #1

3.2a AERIAL VIEW



3.2b DETAIL of TEST SITE

TABLE 3.1

WINTER SEASON CLIMATE DATA* FOR THUNDER BAY

		MONTH						
		O	N	D	J	F	M	A
Air Temp (°C) Airport	Normal	6	-2	-11	-15	-13	-6	-2
	(83-84)	5	-1	-17	-16	-5	-8	5
Cumulative Snowfall (cm)	Normal	3	33	79	127	158	192	208
	(83-84)	8	39	85	115	125	141	145
Sunshine Hours	Normal	128	86	93	118	147	173	215
	(83-84)	134	52	117	119	96	176	249
Cumulative (°C) FDD	Normal	0	60	401	866	1230	1478	0
	(83-84)	0	37	555	1063	1220	1471	0

*Data from Thunder Bay Weather Office and Atmospheric Environment Service, Environment Canada.

3.2 Air Cannon Bubbler System Deployment

The 1984 tests involved installation of an air cannon bubbler system and thermistor arrays, manual measurement of ice thickness, and air photography of ice cover extent.

The bubblers tested during this program were the "burper" type air cannons manufactured by Atara Corporation. Basic components of the bubblers are shown in Figure 3.3, and further specifications are given in Appendix A. Three types of deflectors were used on the air cannons (Figure 3.4).

An array of 10 air cannon bubblers was used in the tests, with 7 located along the north slip wall and 3 in the center. Instrument location is illustrated in Figure 3.5.

The bubblers were installed by cutting a 1.2 m square hole in the ice cover and sinking the bubblers with a steel plate anchor. The bubblers were attached to the anchor with a rope which was adjusted to maintain a diffuser depth of 0.15 m below the ice cover. Vertical positioning was then maintained by the natural buoyancy of the bubbler. Bubbler installation is shown in Figure 3.6.

The anchor ropes were adjusted once during the tests to maintain the prescribed bubbler depth. This was necessary because the suction action of the bubbler eroded the soil around the base of the anchor.

Air was supplied from a central blower via flexible hose. A 20 HP, 575 volt blower maintained a system pressure of 76 kPa (11 psi) at 0.132 m^3/s (280 SCFM), or 0.0132 m^3/s per bubbler. This maintained a mean water flow of approximately 2 m^3/s per bubbler, using Ashton's [12] model for point-source bubblers. Air was supplied to the bubbler system from the morning of March 9 until March 22, 1984.

Water and air temperatures were measured using 8 thermistor arrays, located as shown in Figure 3.5. Table 3.2 gives the thermistor depths for each array. Thermistor data were recorded at half hour intervals from March 8 until March 10, and then at 2 hour intervals until March 23. Data were recorded directly onto floppy disks using a portable data acquisition system.

FIGURE 3.3.

ATARA AIR CANNON BUBBLER

TYPICAL INSTALLATION

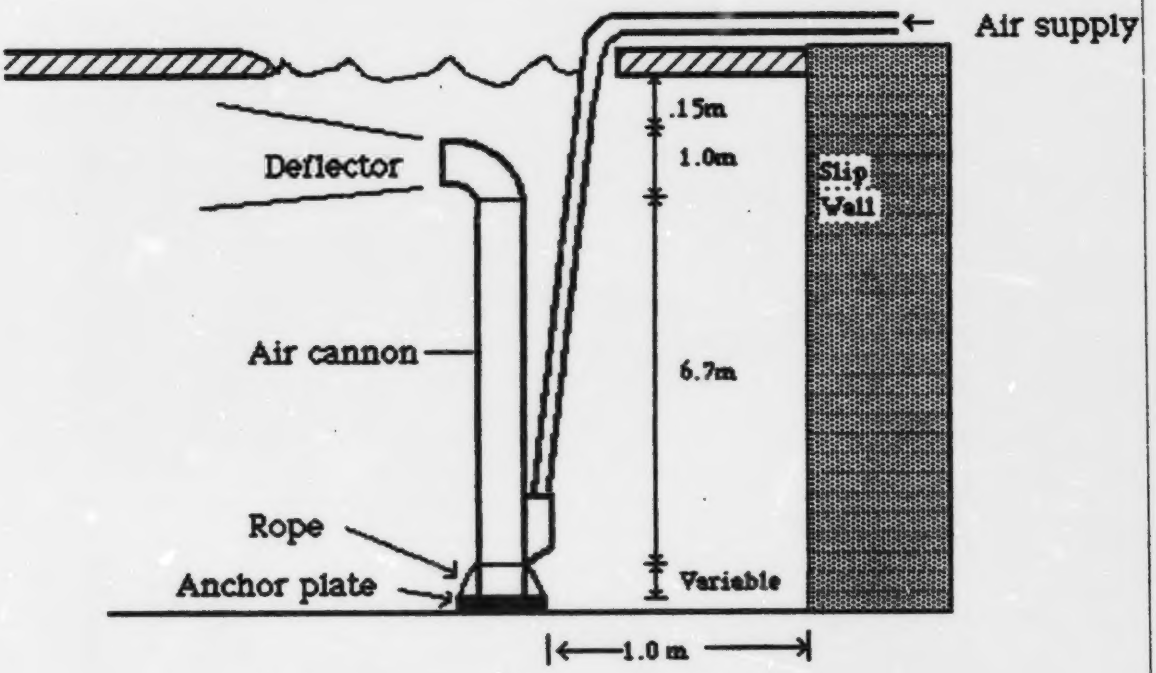
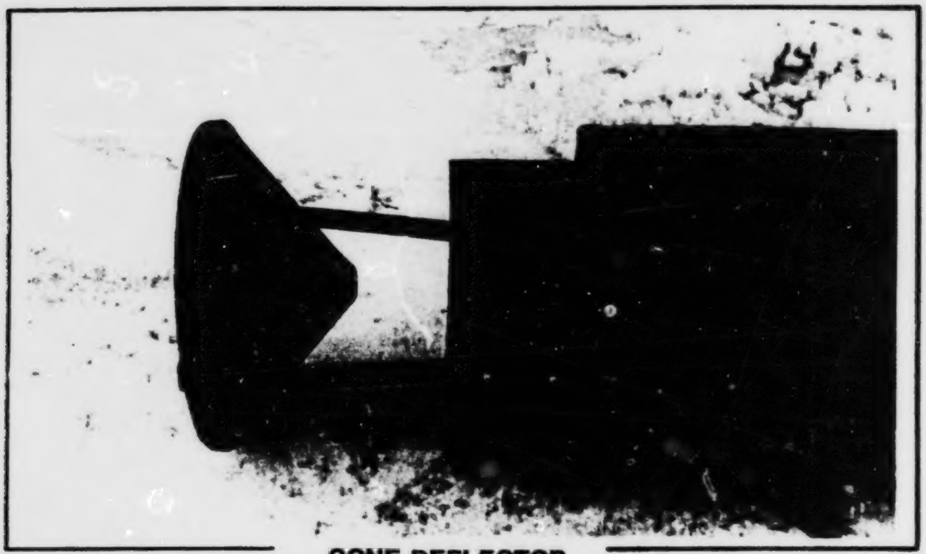
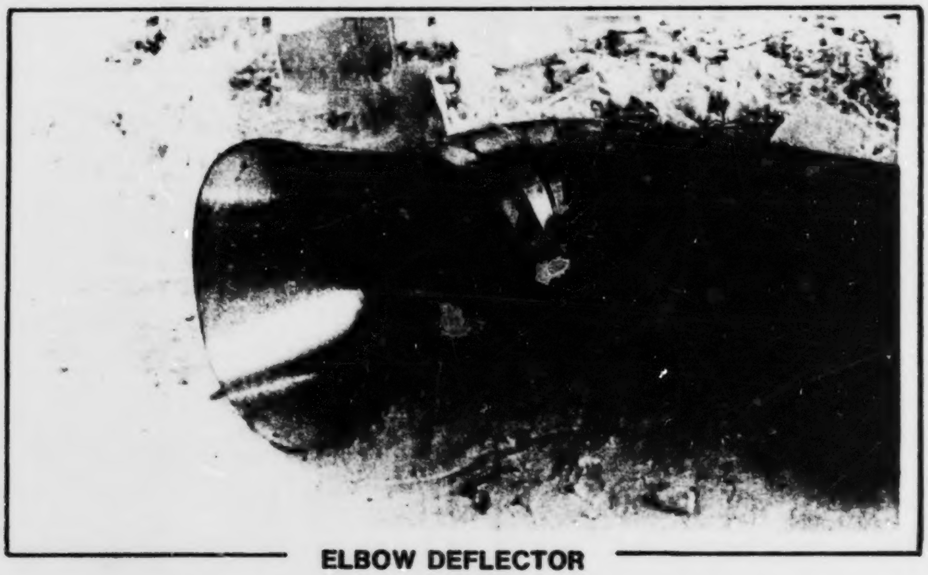

Air supply
Deflector
.15m
1.0m
Slip
Wall
Air cannon
6.7m
Rope
Anchor plate
Variable
1.0 m

FIGURE 3.4 AIR CANNON BUBBLER DEFLECTORS



CONE DEFLECTOR



ELBOW DEFLECTOR

ELBOW DEFLECTOR WITH BAFFLE

FIGURE 3.5

INSTRUMENT LOCATION

CANADA MALTING/SASKATCHEWAN 7B SLIP

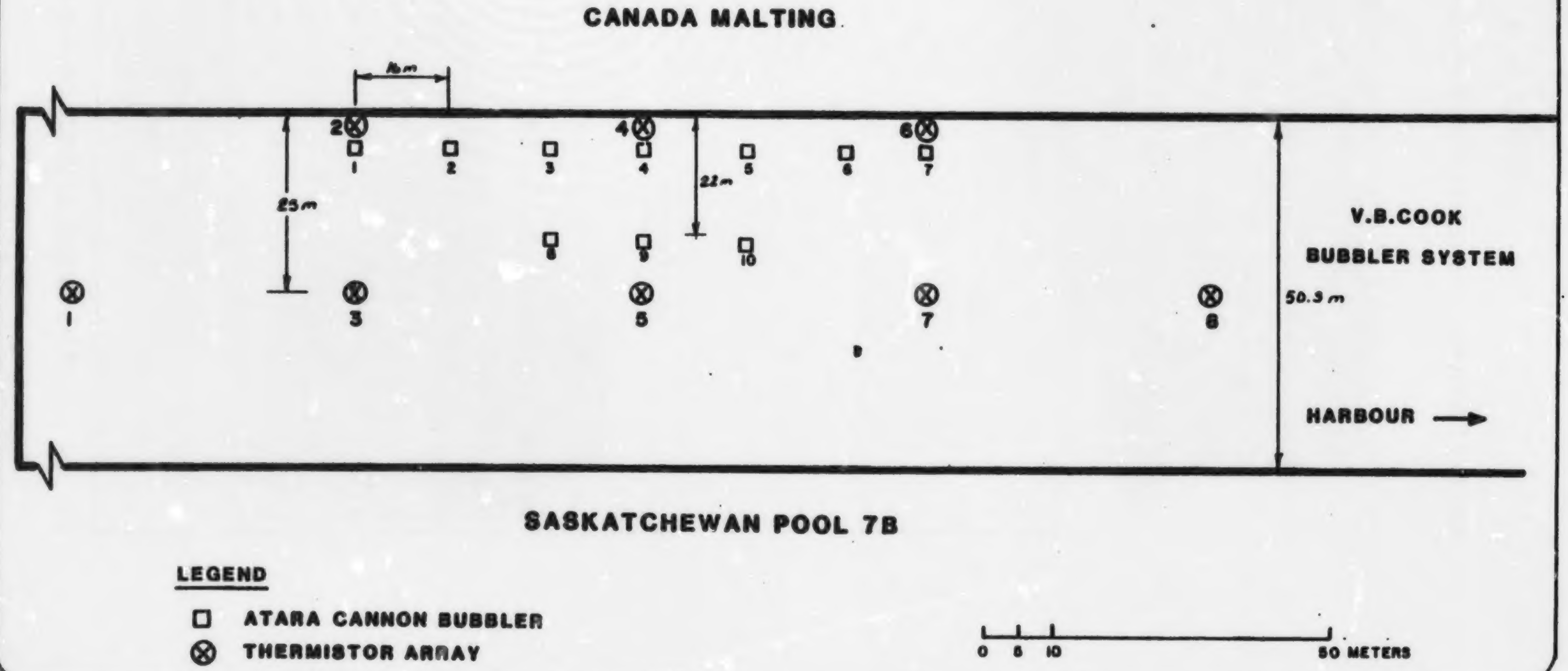
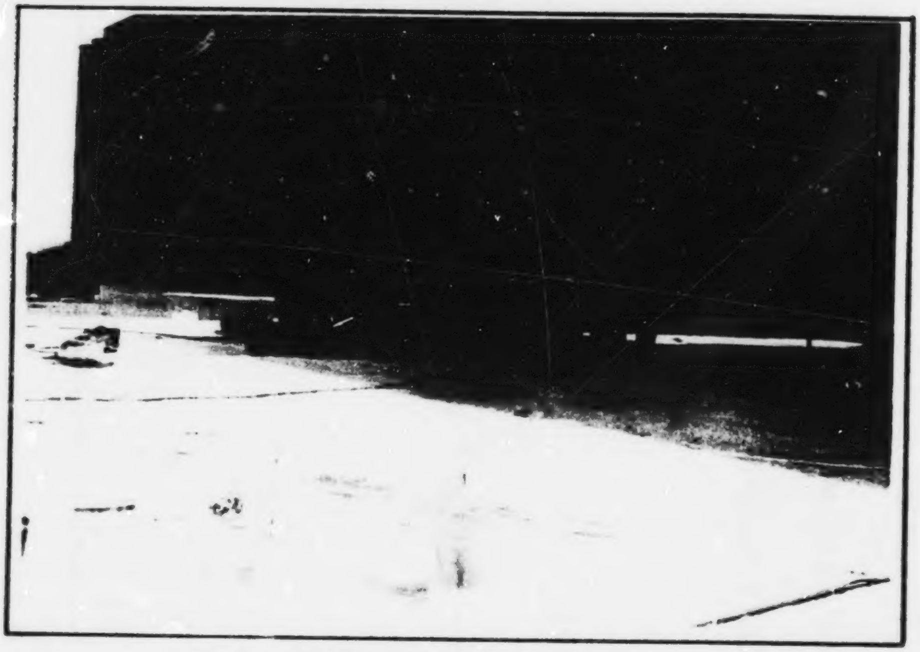
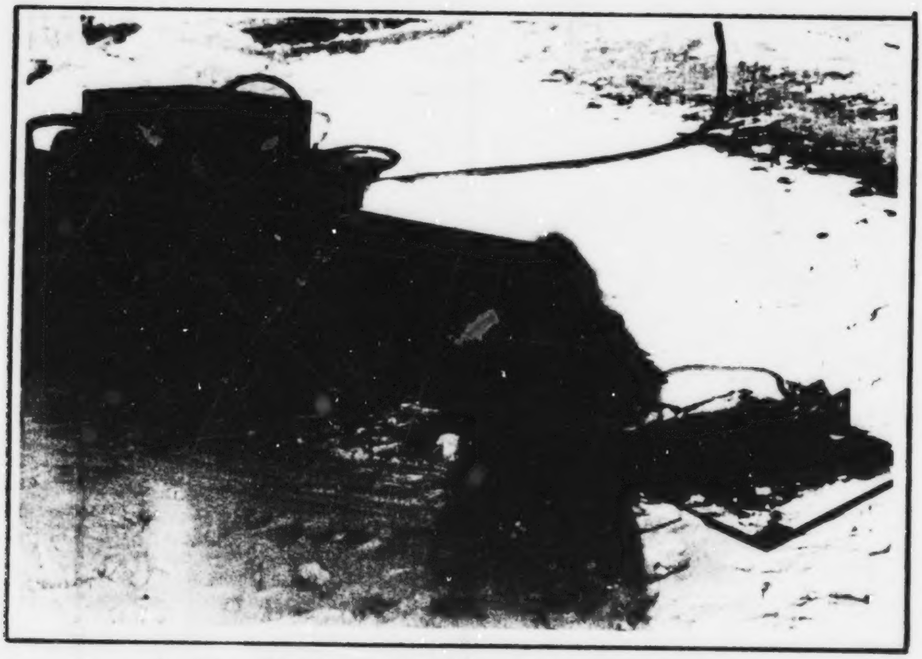

CANADA MALTING
16m
25m
22m
2⊗ 4⊗ 6⊗
1 2 3 4 5 6 7
8 9 10
1 3 5 7 8
V.B.COOK
BUBBLER SYSTEM
50.3 m
HARBOUR ⟶
SASKATCHEWAN POOL 7B
LEGEND
□ ATARA CANNON BUBBLER
⊗ THERMISTOR ARRAY
0 5 10 50 METERS

FIGURE 3.6

INSTALLATION of CANNON BUBBLERS, MARCH 9, 1984



3.6a COMPLETE BUBBLER UNIT



3.6b DETAIL of BUBBLER and ANCHOR

TABLE 3.2

THERMISTOR NUMBERING SYSTEM

ARRAY	THERMISTOR DEPTH			
	AIR	1.0 m	4.5 m	8.0 m
1	1	2	3	-
2	-	4	5	6
3	-	7	8	9
4	-	10	11	12
5	13	14	15	-
6	-	16	17	18
7	-	19	20	21
8	22	23	24	-

Ice suppressions were monitored by manually measuring thickness on March 8, and from vertical air photographs taken at 09:00 hours on March 9, 12, 14, 16, 19, 21, 23, and 26. The photographs incidentally included the "rake" type bubbler tests at the east end of Canada Malting slip and a point source bubbler system at Manitoba Pool #3 slip.

Ice temperatures were measured at an adjacent, nearby slip in association with the ACIB experiments, and are applicable to the Canada Malting slip.

3.3 Air Cannon Bubbler Method of Operating

The cannon bubbler previously used at Thunder Bay was tested along with a point source bubbler under laboratory conditions [10]. The cannon bubbler with a deflector installed showed significantly improved ice suppression and affected a much larger area than did either the cannon bubbler without deflector or the conventional point source bubbler.

The superiority of the cannon bubbler over the point source bubbler is also justified on a theoretical basis:

- The velocity of the induced current under the ice cover is significantly larger for the cannon bubbler because it produces a larger bubble. According to Wegener and Parlange [11] the theoretical velocity of a rising air bubble is described as:

  $$U_B = \sqrt{gr} \qquad (1.1)$$

  where U_B = the rising velocity of the air bubble,
  g = acceleration due to gravity, and
  r = the radius of the bubble.

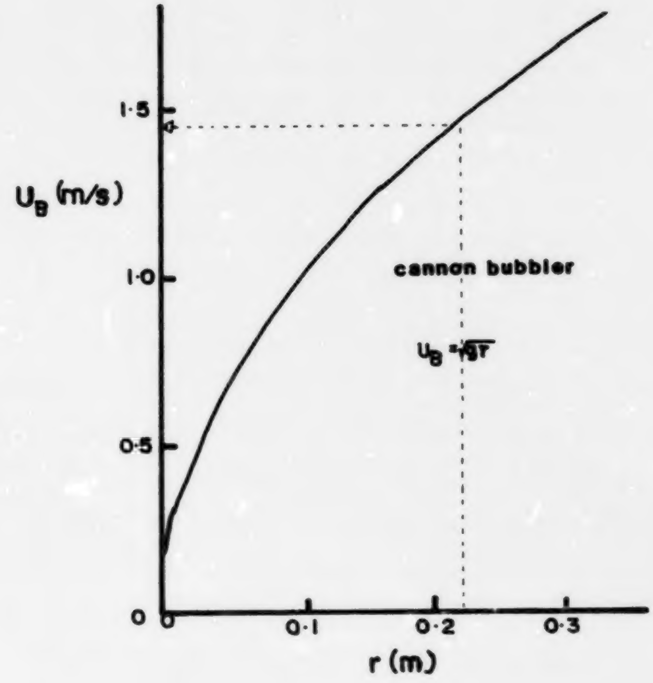
  Figure 3.7 compares the rising velocity for bubbles produced by the cannon and a single point bubbler. Velocity exceeds 1.5 m/s for the former and is less than 0.5 m/s for the latter.

- The efficiency of entrainment in a confined duct such as the cannon bubbler is greater than that from a point source bubbler. The manufacturer of the cannon bubbler states that entrained water velocity is 75 to 80% of the rising bubble velocity depending on the depth of the burper relative to the total depth of the bubbler pipe inlet.

- The higher currents generated by the cannon bubbler are used more efficiently in ice melting. Energy is lost when the rising plume of the point source bubbler impinges on the under surface of the ice. This reduces significantly the ability of the bubbles to entrain water in the horizontal direction. Where open water is present above the rising plume the loss of energy is even higher since the resulting waves are dissipated by gravity and blocked by the ice edge. Loss of energy from the rising plume is less severe for the cannon bubbler because the currents generated can be directed as required using a deflector.

FIGURE 3.7

BUBBLE RADIUS AND RISING VELOCITY



(after Wegener and Parlange [10])

- The higher current velocity generated by the cannon bubbler results in a higher Reynold's number and thus, in a higher coefficient of heat transfer, h. This is shown by Ashton [12] as:

  Average over the impinging area $h_b = 1920\ U_c^{0.62}/b^{0.38}$ (1.2)

  Radial decay $h_r = h_b/(v/b)^{0.45}$ for $r > b_a$

  where U_c is the final velocity of the rising plume and b is a function of the diffusivity for b versus distance from the centre of the impinging point of the water under the ice cover. Since the diffusivity is expected to be smaller for the cannon bubbler, a higher heat transfer can be expected.

In conclusion, theory and laboratory tests both indicated that the cannon bubbler should perform better than conventional bubblers, and it was therefore selected for full scale tests at Thunder Bay.

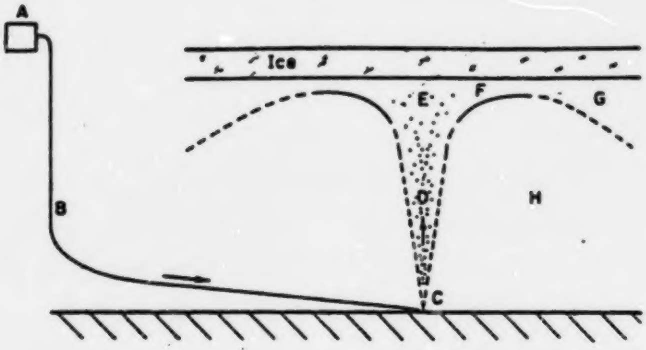
Ashton's theories, developed for line source bubbling systems are illustrated in Figure 3.8 for comparison. A bubble stream forms at the diffuser orifice (C). The bubbles rise and entrain surrounding water. The bubble plume radius expands approximately linearly with height, expanding the radius of entrained water (D). At the surface, the plume spreads laterally creating a convection cell and eventually disperses (E,F,G). Ashton derived numerical models for plume characteristics assuming point and line-source bubblers. If these are applied to the cannon bubblers with air discharge rates of .0132 m^3/sec and orifice depth 8.2 m, the following results are obtained:

- Radius of induced vertical flow: 0.7 m
- Centerline velocity of plume: 0.7 m sec
- Induced flow at water surface: 2 m^3/sec

Ashton's models are shown in Figures 3.9 through 3.12. These models are not exactly applicable to the air cannon bubbler. The centerline velocity and horizontal flow induced at the surface by a cannon bubbler likely exceed that of a line or point source bubbler, and will be underestimated by Ashton's model. Further work is required to fully describe the operation of the air cannon bubbler in a manner similar to Ashton's models for conventional bubblers.

FIGURE 3.8

SCHEMATIC DIAGRAM of the DIFFUSER BUBBLER SYSTEM OPERATION



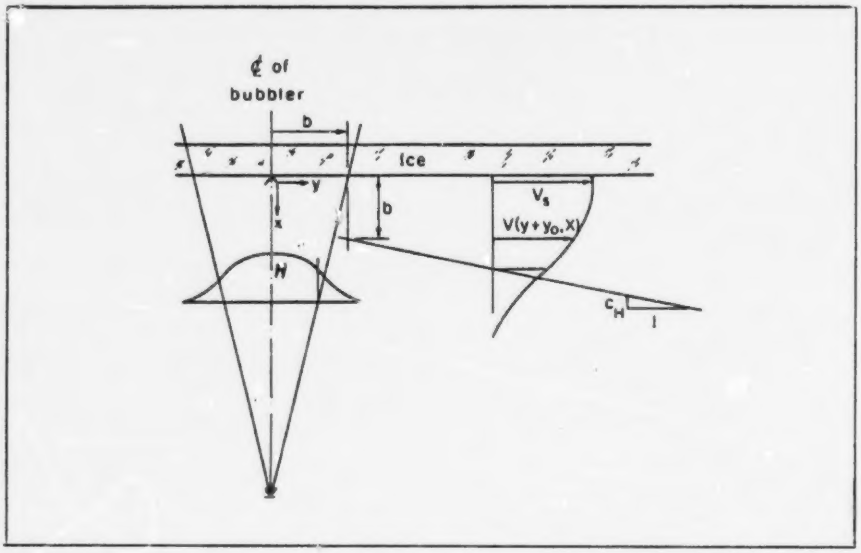
(AFTER ASHTON [12])

A -COMPRESSOR
B -AIR SUPPLY LINE
C -DIFFUSER LINE
D -RISING PLUME OF ENTRAINED WATER
E -PLUME SPREADS UNDER ICE SURFACE
F -REGION OF HORIZONTAL FLOW OF PLUME
G -DISSIPATION OF ENTRAINED WATER

FIGURE 3. 9

DEFINITION SKETCH FOR ANALYSIS OF INDUCED FLOW FOR A LINE SOURCE BUBBLER

(after ASHTON [12])



₵ of bubbler
b
Ice
y
x
b
V_s
$V(y+y_0, X)$
H
c_H
1

FIGURE 3.10

RADIUS OF INDUCED VERTICAL FLOW AT THE SURFACE AS A FUNCTION OF ORIFICE DEPTH AND AIR DISCHARGE FOR A POINT SOURCE BUBBLER

(after ASHTON [12])

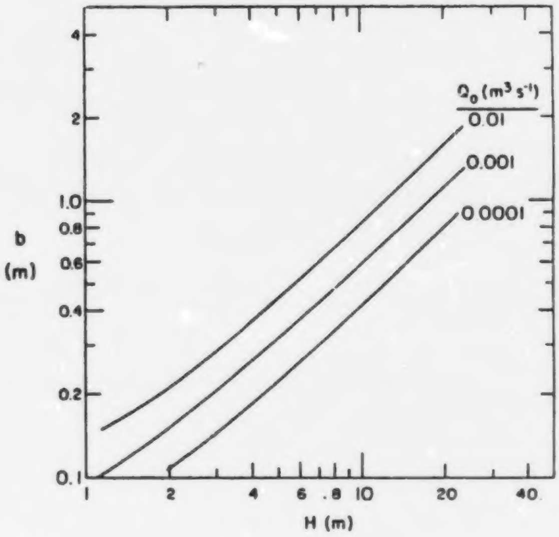


FIGURE 3.11

CENTRELINE VELOCITY OF PLUME AS A FUNCTION OF ORIFICE DEPTH AND AIR DISCHARGE FOR A POINT SOURCE BUBBLER

(after ASHTON [12])

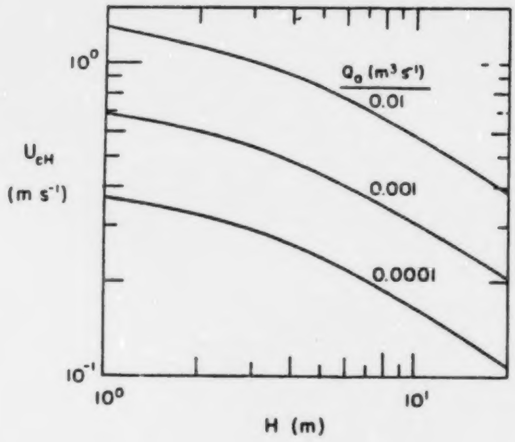
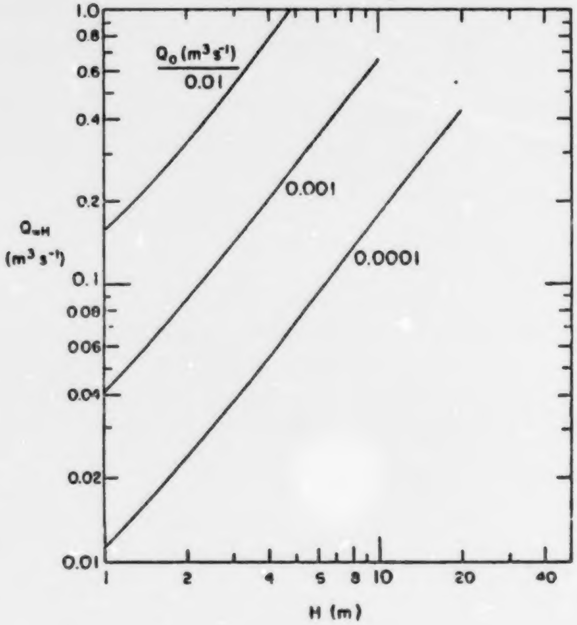


FIGURE 3.12

INDUCED FLOW AT WATER SURFACE AS A FUNCTION OF ORIFICE DEPTH AND AIR DISCHARGE FOR A POINT SOURCE BUBBLER

(after ASHTON 12)



3.4 Other Systems Deployed in Thunder Bay Harbour

Two other systems were deployed during the same period in Thunder Bay Harbour. The following is a brief description of each system:

3.4.1 "Rake" Type Bubbler Tests

V.B. Cook tested a "rake" type bubble diffuser system at the east end of the Canada Malting slip. The diffuser pipes were supported by barrels set up in a sled-like configuration (Figure 3.13). Basically, the diffusers were set below the edge of the ice cover. The ice was gradually melted away from the diffusers, and the sled was then manually dragged along to re-set the diffusers below the ice edge. The system was designed in this manner for two reasons. First, the barrels facilitated installation and removal of the system and second, a larger area could be melted than is possible with a stationary system of the same size and type.

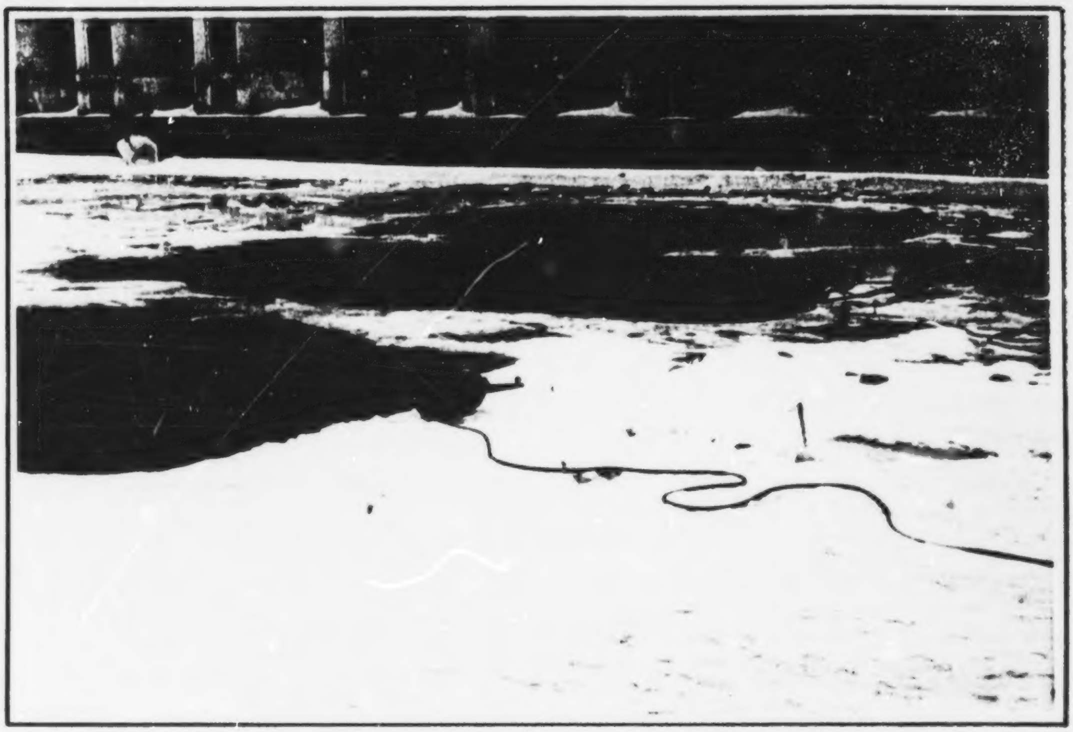
The system was installed on March 1 and was dragged forward periodically thereafter. Compressed air was supplied at a rate of 90 SCFM (personal communication, V.B. Cook Company Ltd.), and pressure of 690 KPa using one 40 HP compressor [3].

3.4.2 Manitoba Pool #3 System

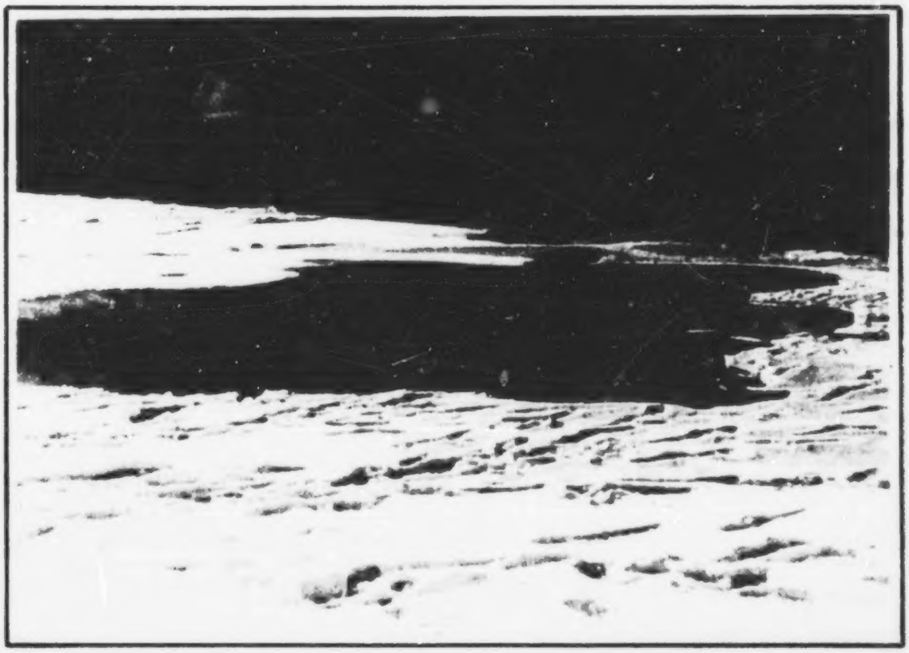
The air photographs in (Appendix B) show an ice melting system in operation at Manitoba Pool #3. It was a point source bubbler comprised of three, 40 foot garden hoses anchored about 20 feet below the ice surface. Manitoba Pool operates a similar system every year, with 3 to 5 hoses anchored 15 to 20 feet below the ice and moved every 1 to 2 weeks. Air is supplied by a compressor in the workhouse (personal communications, Mr. G. Cooper).

FIGURE 3.13

DETAIL of "RAKE" SYSTEM INSTALLATION



a RAKE DIFFUSERS PULLED AGAINST ICE COVER



b ICE COVER MELTED AWAY FROM DIFFUSER

4. RESULTS

4.1 Evaluation Criteria

Measurements of water temperature and ice melting during the experiment allow an evaluation of ice suppression using air bubblers according to several criteria. These include:

1. Effect of bubbler on water temperature and circulation
2. Thermal reserve available for melting ice.
3. Effect of deflectors on development of horizontal flow.
4. Ice melting capability and efficiency.

Experimental results are described below in terms of each of these criteria.

4.2 Effect of Bubbler on Water Temperature and Circulation

4.2.1 Comparison of Water Temperatures in Elevator Slips and Harbour

Water temperatures have been measured daily in Thunder Bay Harbour since at least 1969 (personal communication, R. Romanek, City of Thunder Bay). Monthly averages from the Bear Point water intake for 1983 and 1984 are given in Table 4.1. According to water plant personnel, year to year variations in winter months are negligible. Maximum day to day fluctuation was 0.5°C during February and less than 0.0°C during March, 1984.

In Table 4.2, water temperature in the harbour is compared with available measurements in several elevator slips, and with ice thickness measurements. The available data do not allow statistical comparison of harbour and slip temperatures, but suggest that more variability occurs in the slips than at depth in the harbour, and also that temperature varies from slip to slip. Such a pattern should be expected; temperatures are relatively constant outside the breakwater where the deep lake water has a moderating effect, and are both colder and more variable within the breakwater, where the deep lake waters do not circulate.

TABLE 4.1

WATER TEMPERATURES AT THUNDER BAY HARBOUR (°C)

	MONTH											
YEAR	J	F	M	A	M	J	J	A	S	O	N	D
1983	4.19	4.50	4.79	5.28	7.41	10.13	12.63	13.19	12.27	10.29	8.77	5.53
1984	4.58	4.70	5.00									

Location: Bear Point water intake 720 m offshore and outside harbour breakwater.
Depth of intake is 9m; 15 m above lake bed.

TABLE 4.2

COMPARISON OF TEMPERATURE AND ICE COVER DATA

LOCATION/PARAMETER	MARCH 1984	MARCH 1983	MARCH 1982	LONG TERM
Harbour T °C *	5.00	4.79		
Airport CFDD (°C)	1471	1061	1318	1500
Water Temp. In Slip (°C)				
Can.Malting	1.17			
Cargill		.73		
U.G.G.		.24		
Saskatchewan #7A		.40		
Mean Ice Thickness (cm)				
Harbour	64	61	79	78 ± 13
Manitoba #1	80			
Can.Malting	65			
U.G.G.		74		
Saskatchewan #7A			75	

* at Bear Point water intake.

4.2.2 Temperature During Bubbler Tests

Variability of Temperatures

Figure 4.1 illustrates water temperatures and other environmental data during the tests. Wind, sunshine and air temperature are from Thunder Bay Airport, while water temperatures are from Array #2 at the test site. Water temperatures at this array ranged over time from 0.75°C to 1.3°C.

Water temperatures at the Canada Malting Slip in 1984 were higher than those measured at other slips in 1983, but showed a similar variation. Temperatures prior to bubbling in 1984 ranged from 0.7 to 1.2°C, while in 1983 the range was 0.10 to 0.50°C at Saskatchewan #7A and 0.70 to 0.76°C at Cargill [5].

Warmer water temperatures during 1984 might be explained by a warmer than normal summer in 1983, by unusually warm and rainy weather experienced in February 1984 (personal communication, Thunder Bay Weather Office) or by a discharge of surface water into the slip from the Saskatchewan Pool elevator (see aerial photographs).

Effect of Bubbler Operation on Temperature Profiles

Figure 4.2 shows temperature profiles for all thermistors at three time periods: prior to bubbling; one day after bubbling began, and; eleven days after bubbling began. These three time periods show the short and long-term effects of bubbling on the water temperature structure in the slip.

Prior to bubbling, two types of temperature profiles are evident. Thermistor arrays #4, 5, 7, and 8 show an isothermal profile at about 1.20°C. Arrays #3 and 6 have an isothermal bottom layer at about 1.20°C and a cold surface layer with temperatures about 0.80°C at 1 metre depth. Arrays # 1 and 2 appear to follow the latter model although measurements at 8.0 m depth are not available.

Temperature profiles 1, 2, 3 and 6 approximate the model proposed by Ashton [11] and others, in which cooler, less dense water forms a surface layer which is isolated from warmer, more dense water at the bottom. The bottom water thus forms a thermal reserve. The reason for isothermal profiles at arrays, 4, 5, 7 and 8 was not investigated in the field. Possible explanations include: prior mixing due to the operaton of a bubbler system at the east end of the slip beginning March 1; mixing due to the inflow of surface water from Saskatchewan Pool elevator; local wind or current effects.

The spatial pattern of water temperatures at 1 metre depth (i.e. near surface) is further illustrated in Figure 4.3. Again, this pattern is not explained by the data measured but could result from the water discharge from Saskatchewan Pool # 7B (see photos in Appendix B), or from previous operation of a bubbler system at the east end of the slip.

FIGURE 4.1

TEST ENVIRONMENTAL DATA

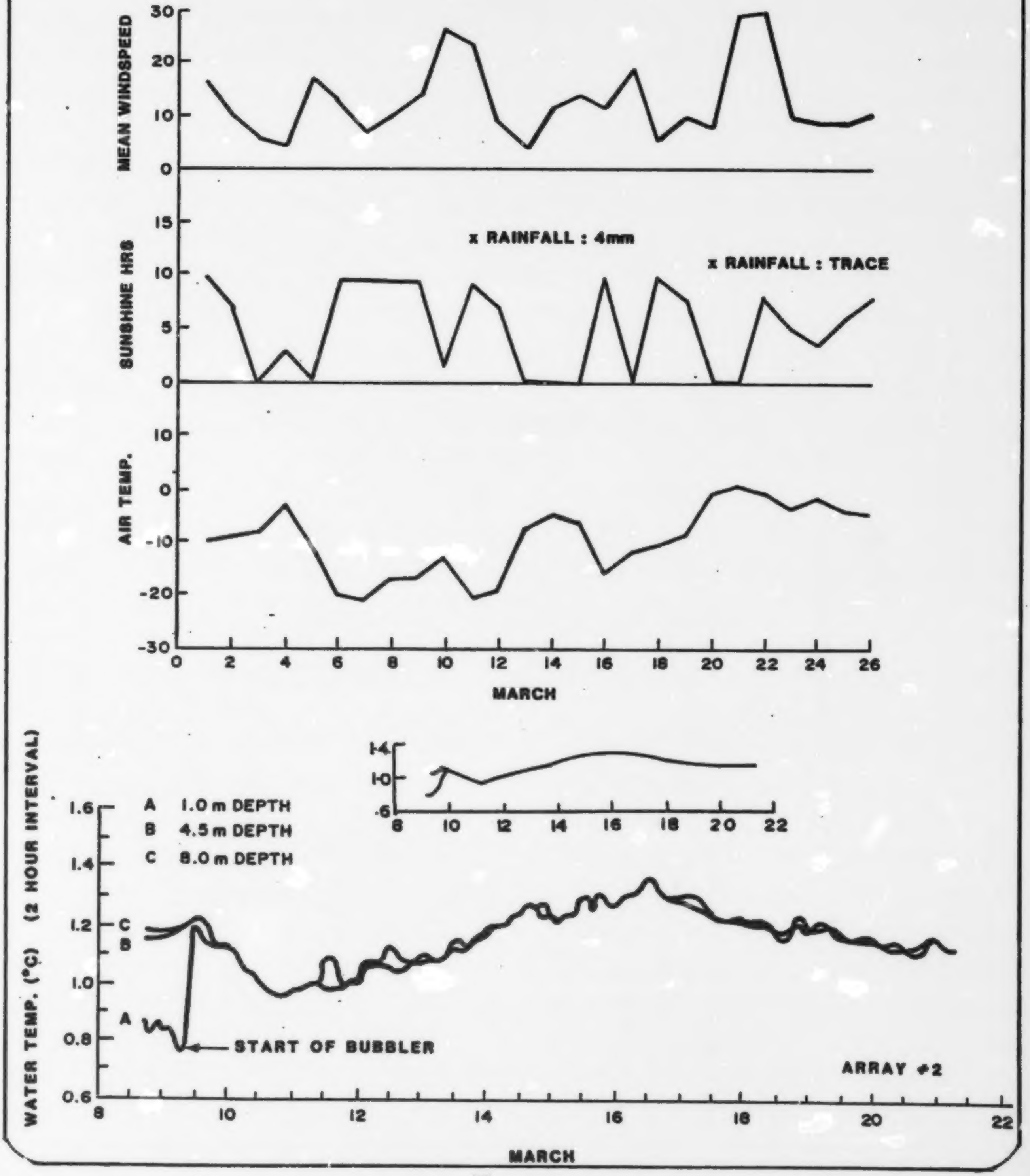
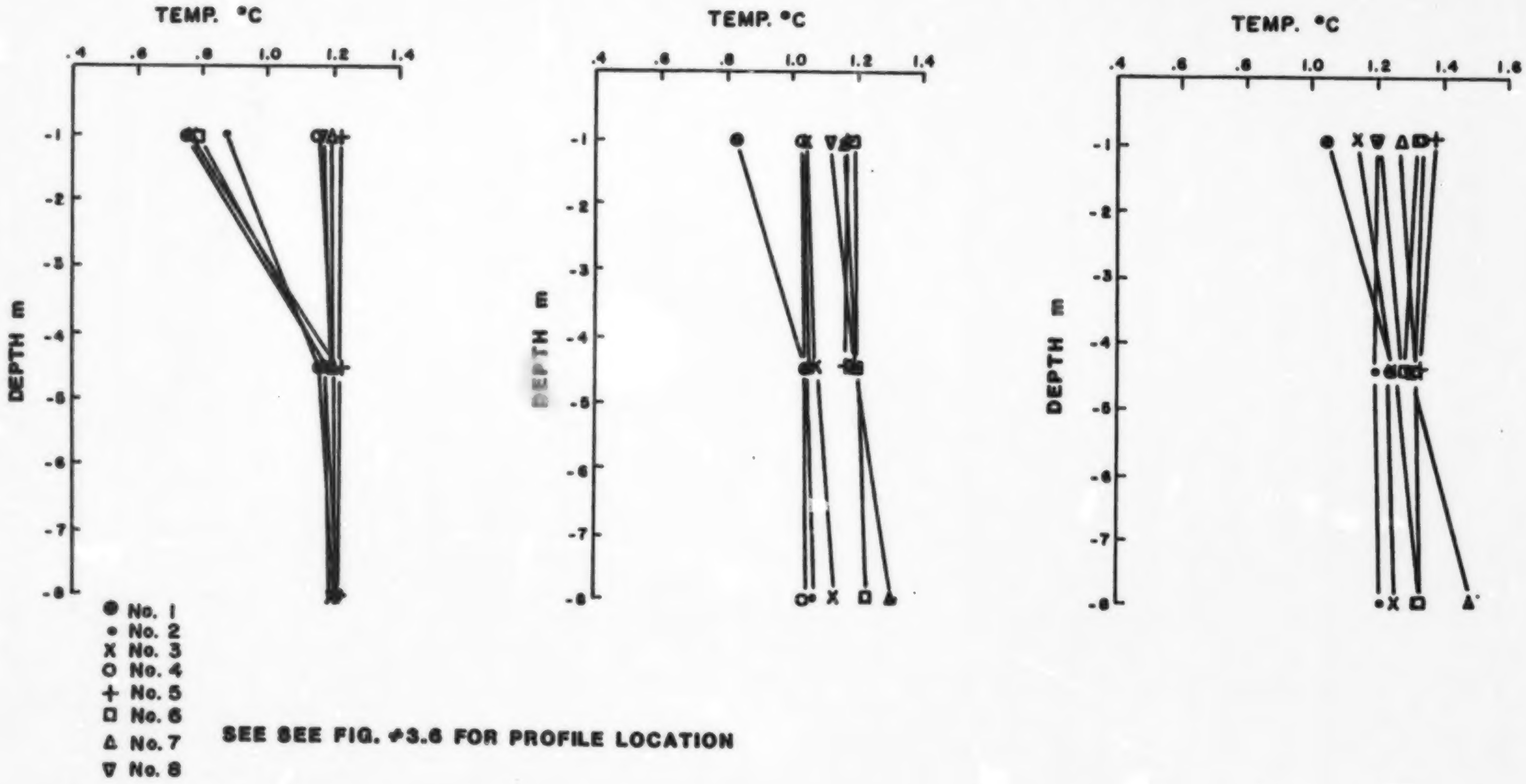


FIGURE 4.2

WATER TEMPERATURE PROFILES for CANADA MALTING SLIP



4.2a MARCH 8, 1984 6:00 PM

4.2b MARCH 10, 1984 6:00 AM

4.2c MARCH 21, 1984 6:00PM

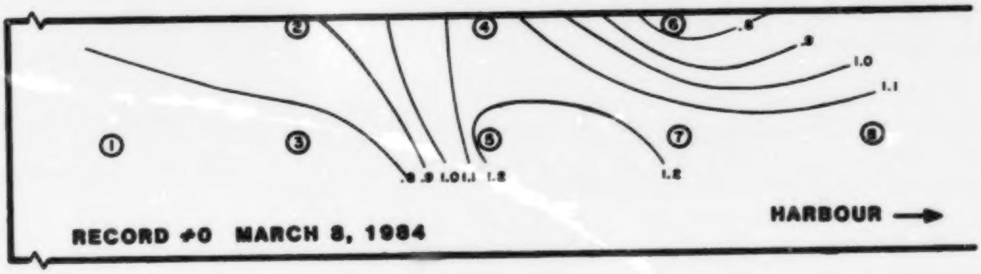
SEE SEE FIG. #3.6 FOR PROFILE LOCATION

FIGURE 4.3

CONTOURS OF WATER TEMPERATURE at 1m DEPTH

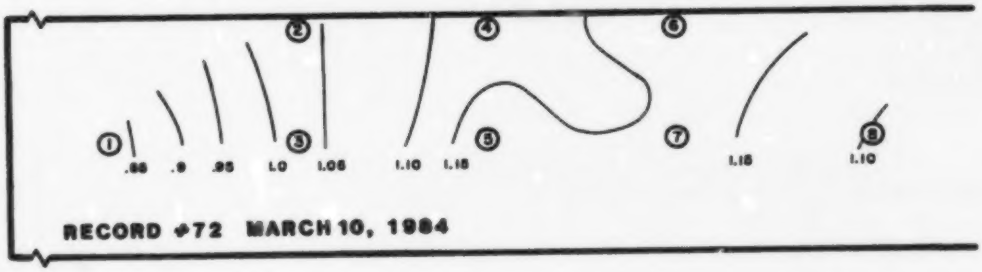
(a)

CANADA MALTING

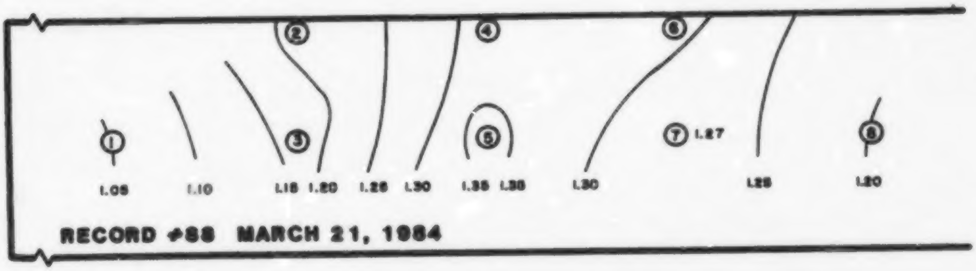


SASKATCHEWAN POOL 7B

(b)



(c)



4.3 Thermal Reserve

Bubbler theory holds that ice is melted when the bubbler creates a convection of warm, bottom water to the ice cover, and the capability of a bubbler system will therefore be limited by the reserve of warm water available at the site. The thermal reserve at the Thunder Bay slips was estimated using measured temperature profiles, to evaluate its effect on ice suppression.

Abdelnour [5] found that the thermal reserve in the water alone prior to bubbling in 1983 was sufficient to melt about 10% of the total ice cover. Similar calculations for 1984 are illustrated in Figure 4.4., which compares the thermal reserve at four time periods with the heat energy actually used to obtain the observed melting. The thermal reserve prior to bubbling in 1984 was sufficient to melt about 17% of the total ice cover, assuming ice at 0°C and no heat loss to the air.

Figure 4.4 shows that the heat content after March 13 was insufficient to explain the melting that actually took place, and also that the heat content increased over time. Heat was obviously added to the slip during the experiment.

The scope of the field program did not entail measurement of sources of heat input to the slip, but observations from other experiments provide several possible sources. Observations of spatial patterns of melting in 1982 suggested that heat conduction from the slip walls could be important [4]. Measurements in 1983 [5] as well as measurements in the harbour (Table 4.2), indicated that deeper water outside the slip was warmer. Mixing of this water with that in the slip is therefore one possible source of heat input. Another possible source is a surface water discharge which was observed on the 1984 air photographs (Figure 3.8). Finally, ice temperature measurements at an adjacent slip indicate that direct solar heating plays an important role in warming the ice surface, and could be responsible for ice melting during the test period (Figure 4.5). Ice thickness measurements at the test sites and in Thunder Bay harbour (Figures 4.6 and 4.7) do not show significant melting during the test period (personal communication, Thunder Bay Weather Office), and this suggests that the solar heating contributed to the melting process but did not in itself provide significant melting.

In conclusion, observations in 1983 and 1984 indicate that initial temperatures and heat content of the slip are not limiting factors in the ice melting capability of the bubbler at Thunder Bay.

FIGURE 4.4

HEAT CONTENT in SLIP

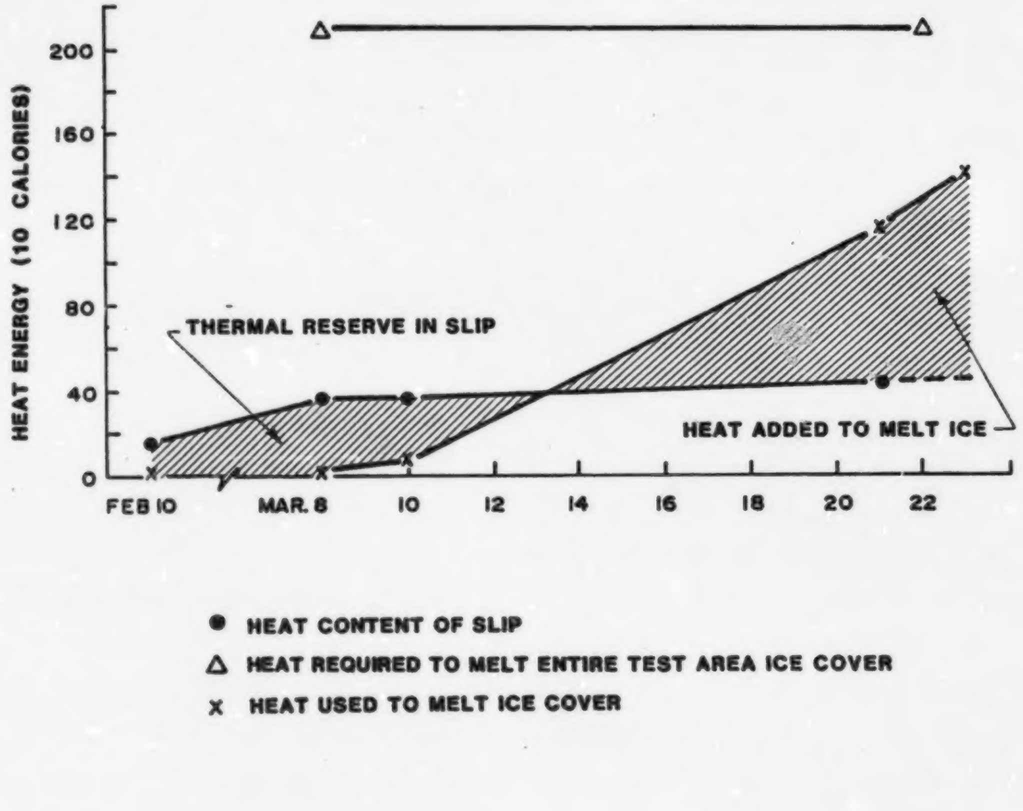


FIGURE 4.5

ICE TEMPERATURE PROFILES at MANITOBA POOL #1, MARCH 1984

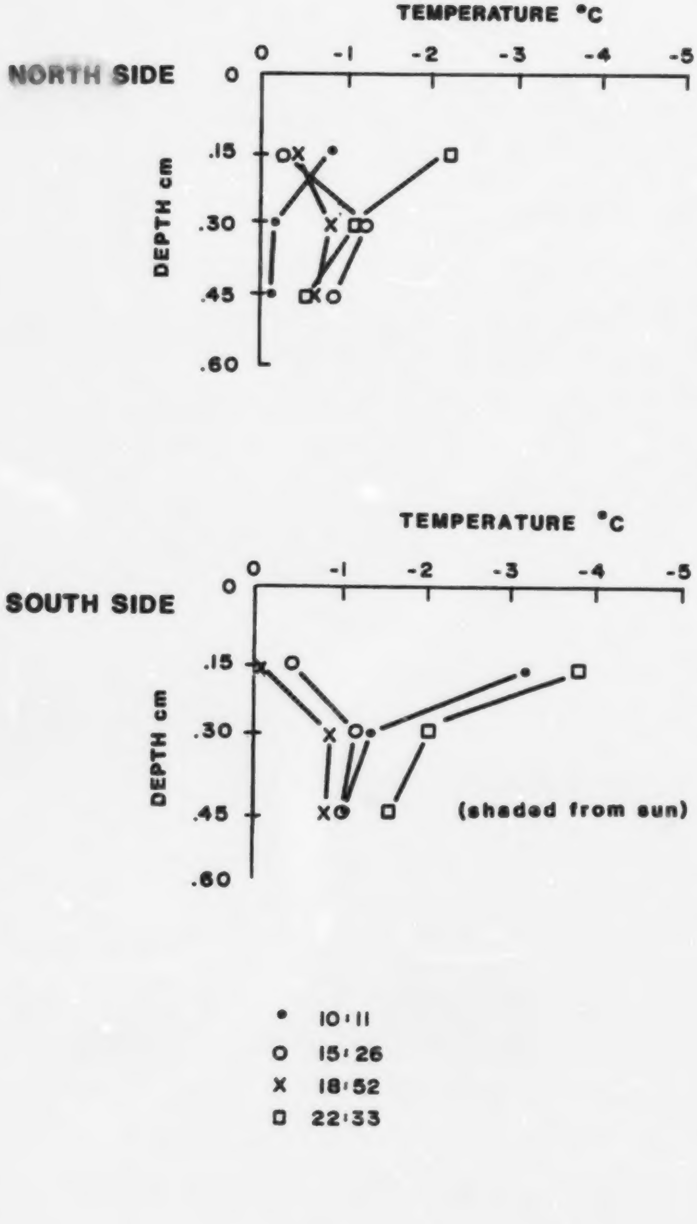


FIGURE 4.6

ICE THICKNESS at CANADA MALTING SLIP, MARCH 8, 1984

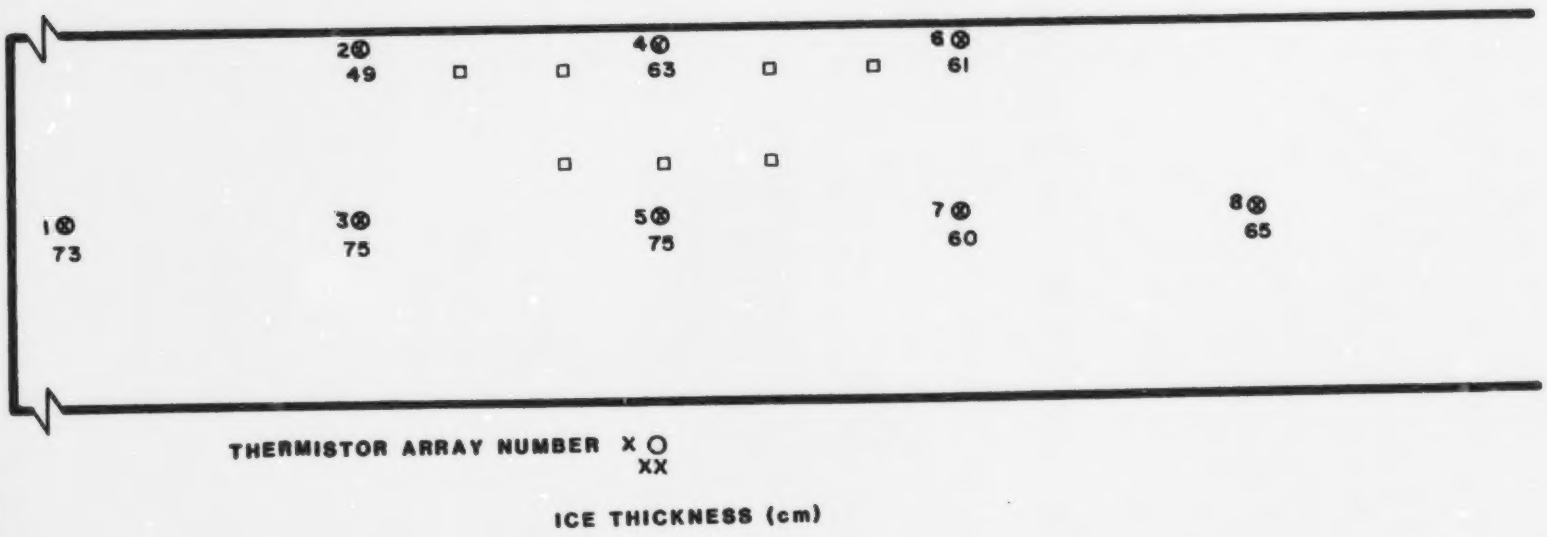
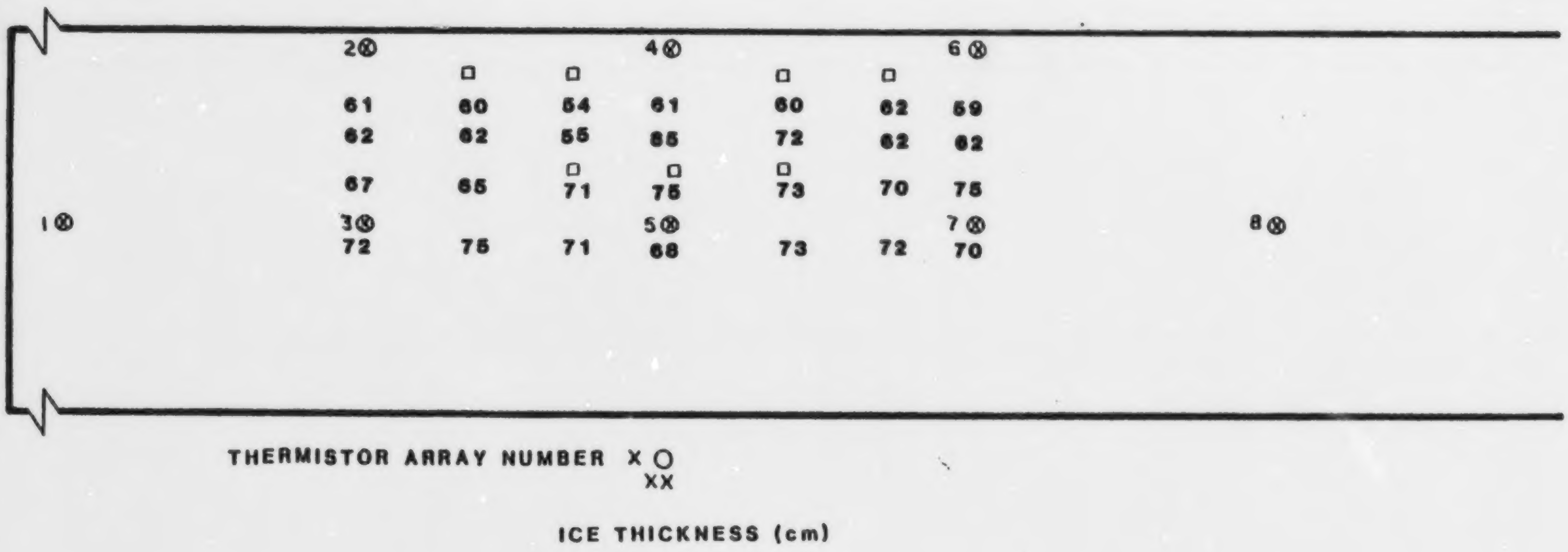

1⊗ 73
2⊗ 49
3⊗ 75
4⊗ 63
5⊗ 75
6⊗ 61
7⊗ 60
8⊗ 65
THERMISTOR ARRAY NUMBER X○ XX
ICE THICKNESS (cm)

FIGURE 4.7

ICE THICKNESS at CANADA MALTING SLIP, MARCH 9, 1984


1⊗
2⊗
4⊗
6⊗
□ □ □ □
61 60 54 61 60 62 59
62 62 55 85 72 62 62
□ □ □
67 65 71 75 73 70 75
3⊗
5⊗
7⊗
8⊗
72 75 71 68 73 72 70
THERMISTOR ARRAY NUMBER X ○
XX
ICE THICKNESS (cm)

4.4 Effect of Deflectors on Development of Horizontal Flow

The mechanism of ice melting by the cannon bubblers was observed visually during the field experiment. Three mechanisms were noted (Figure 4.8):

- melting of the ice sheet at the bubbler hole edge
- melting of the underside of the ice sheet edge for a radius of about 2 m from the hole
- melting of the upper surface of the ice sheet by wave overtopping. This is enhanced by the bubbling mechanism of the air cannon design.

All three mechanisms were observed at one hole.

Theoretical considerations described in Section 3.3 earlier, and previous laboratory tests [10] indicated that air cannons with deflectors develop a better horizontal flow than do conventional bubblers or air cannons without deflectors. Direct measurement of horizontal flow developed by the air cannons was not possible, but two indirect observations support the conclusions of the previous work.

First, thinning of the ice two metres from the edge of the bubbler holes was observed. Repeated measurements of the radius of thinning were not possible for safety reasons, but the visual observations suggest that horizontal flow did occur.

Second, increased water temperatures were noted 48 m from the nearest bubbler, and this could result from horizontal flow induced by the bubbler.

4.5 Ice Melting Rate and Efficiency

Rate of Ice Melting

The overall rate of ice melting was determined by measuring the change in open water areas on air photographs (Appendix B).

Ice thickness was measured at Canada Malting slip prior to the tests (Figure 4.7), after one day of bubbling and at the conclusion of the tests. Mean thickness prior to the tests was 65 cm, and showed no difference beyond the accuracy of measurement at the latter two times. Likewise, ice thickness in the harbour ranged from 61 to 64 cm between March 9 and 30, with no apparent trend over time (personal communication, Thunder Bay Weather Office).

As the above measurements indicated no natural thinning of the ice cover during the test period, and the extent of thinning around the bubbler holes could not be measured, ice thickness was assumed constant at 65 cm for purposes of calculating melting rates. This results in conservative estimates of ice melting, since field and laboratory [10] observations indicate that the air cannon bubblers do melt the underside of the ice cover.

FIGURE 4.8

BUBBLER HOLE, MARCH 10, 1984

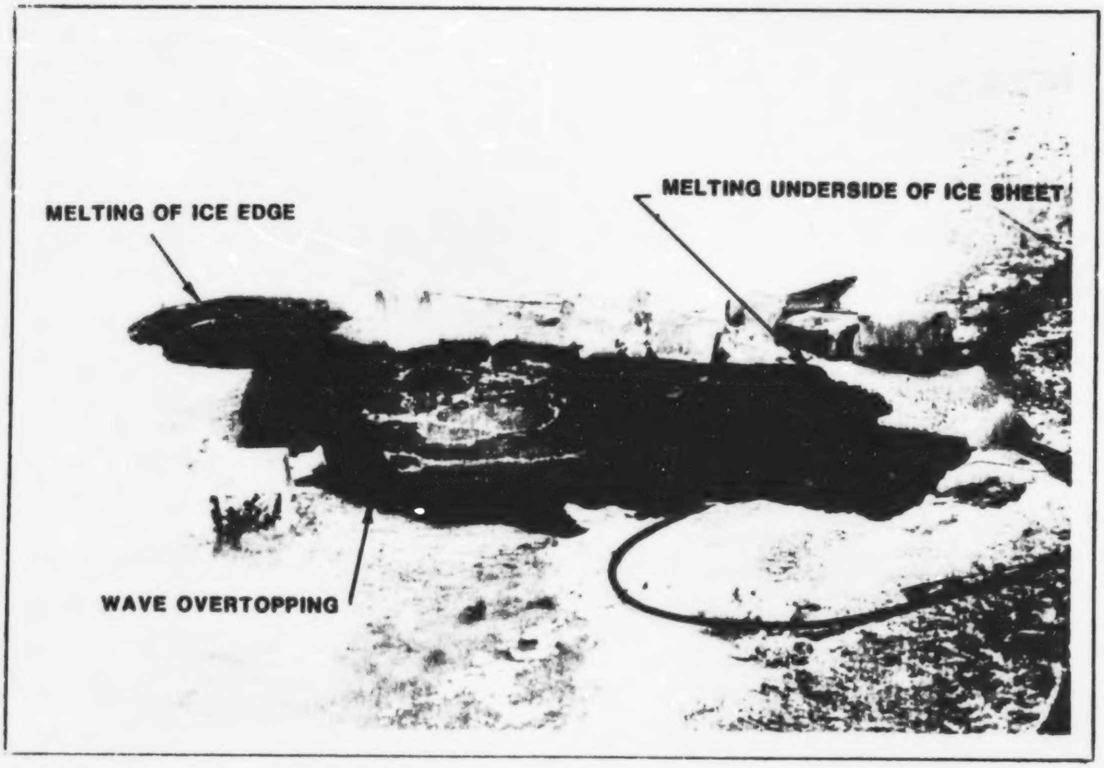

MELTING OF ICE EDGE
MELTING UNDERSIDE OF ICE SHEET
WAVE OVERTOPPING

Figure 4.9 compares the cumulative area melted by each of the air cannon, "rake" diffuser and point source bubbler systems. The cannon system clearly melted the largest area of ice overall and showed the highest rate of melting through most of the test period, with an overall average rate of 193 m²/day.

The "rake" diffuser system operated for a longer time period (started bubbling March 1) and melted less ice. The average melting rate for the diffuser system was 82 m² day, and the point source bubbler melted 17.8 m² of ice per day, after bubbler holes became visible in the air photographs.

The air cannon system used an air supply rate of 0.132 m³/s at 76 kPa, while the "rake" diffuser system used a rate of 0.040 m³/s at pressure of 690 kPa. The air cannon thus melted 0.017 m² of ice per m³ of air to the rake diffuser's 0.23 m² per m³. The efficiency of the air cannon system is higher however, because less energy is used to supply air at lower pressure. The air cannon system used a 20 HP blower while the rake diffuser used one 40 HP compressor [3]. Air supply to the point source bubblers was not known.

Variations in Melting Rate

Previous work [7, 8, 10] indicates that water and air temperatures and wind speed can limit the capability of a bubbler system to suppress ice, and affect the rate of melting. Variations in melting rate for each bubbler system at Thunder Bay are shown in Figure 4.9. Small variations are shown for the cannon and point source bubbler systems, while the rake system showed large variations in melting rate. Between March 16 and 19, part of the rake system bubbler hole was covered with new ice (not shown on graph) and a minimal area of additional melting occurred.

Comparison of melting rates in Figure 4.8 with environmental parameters in Figure 4.1 shows little correlation. For the cannon bubbler higher melting rates occur during periods of high air temperature, with sunshine and wind speed having no consistent relationship.

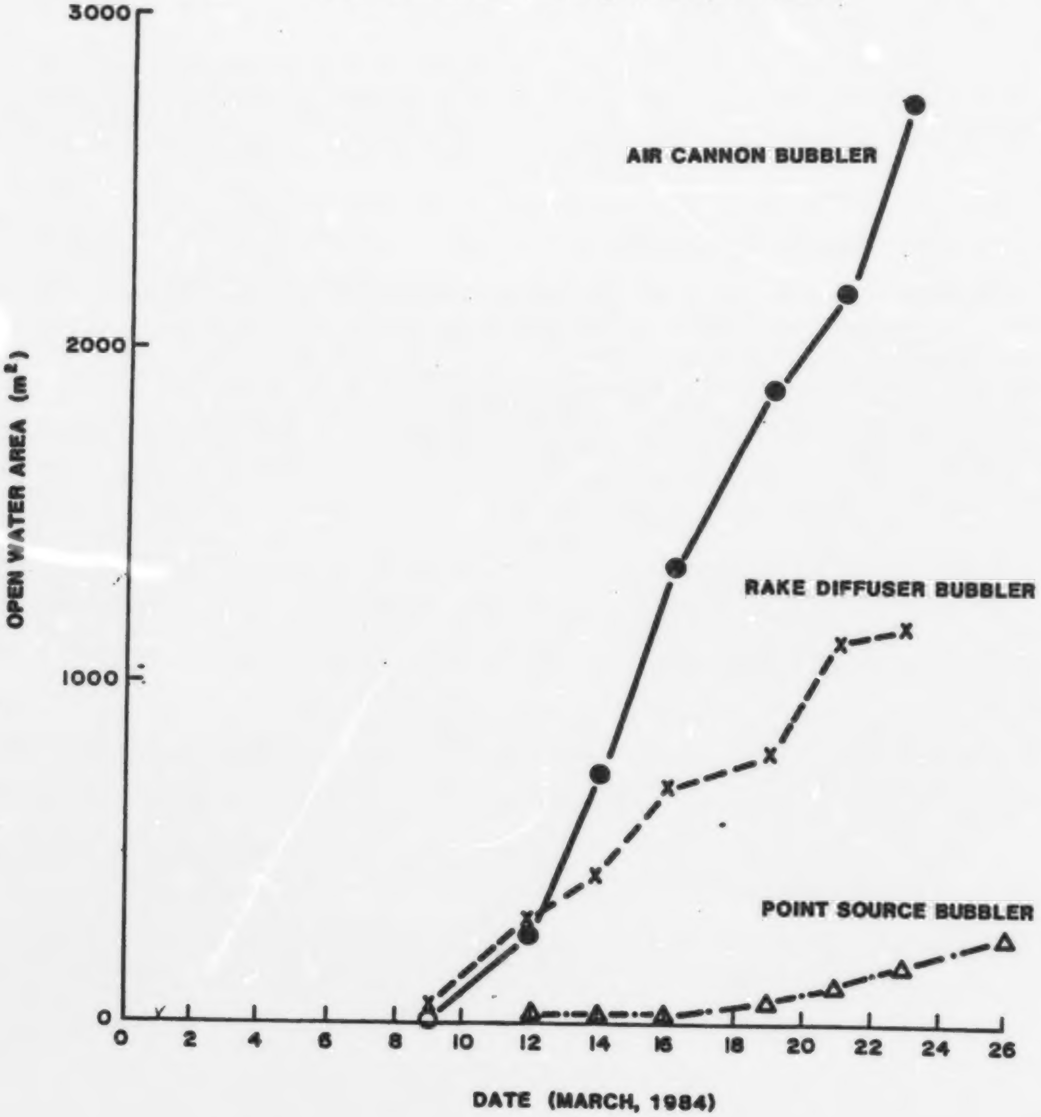
For the rake system, no consistent relationship is apparent between melting rates and environmental parameters. Relationships in this case could be obscured by the schedule of re-positioning of the bubbler system as described in section 3.2.3 above.

The point-source system melting rate shows no apparent relationship with environmental parameters.

Melting rates show variability over a time scale of days, but the variability for each bubbler is not closely correlated with individual environmental parameters. The point source system shows the least variability in melting rates and the rake system shows the highest variability.

FIGURE 4.9

AREA MELTED by THREE DE-ICING SYSTEMS AT THUNDER BAY, MARCH 1984



4.6 Cost Analysis

Costs involved in clearing ice from the Canada Malting slip during the 1984 air cannon bubbler tests are given in Table 4.3 (column A). The breakdown includes capital, deployment, operating and maintenance costs, using the following criteria:

- Capital costs include a 10-unit system with air cannon bubblers, deflectors, cannon anchor plates, compressor (blower), manifold, compressor hut, piping and hardware. The manufacturer's design and development costs are also included in the system cost.
- Deployment costs include manpower and machinery to install the bubblers in the harbour slip and to remove the bubblers at the end of the ice clearing season.
- Operating costs include energy used by the compressor or blower.
- Maintenance costs include labour involved in adjusting the air supply and in repositioning the bubbler during the ice clearing season, after the initial deployment. Costs associated with testing (as opposed to operating) the bubbler system are not included.

These costs are for a prototype system which melted approximately 2750 m^2 of ice cover in the slip in March, 1984. Costs associated with an operational system would be reduced from the above, for several reasons.

First, the capital cost quoted above included unspecified charges for design and development. It is hypothesized that a similar system could be purchased with lower associated design and development costs. Second, capital costs would be amortized over the life of the bubbler system. Third, the deployment costs would be reduced from year to year as experience was gained in handling the equipment. Fourth, the air cannon system tested melted more ice than other systems tested in 1984 or in previous years, and possibly more than is required for entry of a ship. Costs could be reduced using an air cannon system with fewer bubblers or with a shorter period of operation, if more ice than necessary was melted.

The relative effects of each of these factors on the annual cost of the air cannon bubbler system are illustrated in Table 4.3. In column B, our estimate of the hardware costs minus design and development costs, are presented. In column C, capital costs for the system in column B are amortized over 5 years in 1984 dollars and without interest, to show the estimated annual cost of the system. In column D, the deployment cost represents the average annual cost when deployment cost is reduced at the compounded rate of 5 percent per annum. Finally, column E shows the estimated cost of a 5-unit system of air cannon bubblers using the same assumptions as column D, and some educated guesses as to proportional reductions from the 10-unit system.

TABLE 4.3

AIR CANNON BUBBLER SYSTEM COST COMPARISON

COST ITEM	A PROTOTYPE 10-UNIT AIR CANNON	B PRODUCTION AIR CANNON	C ANNUAL COST 5-YEAR AMORTIZATION	D ANNUAL COST MINUS 5% LEARNING	E COLUMN 'D' FOR 5-UNIT SYSTEM[4]
CAPITAL	$46,000[1]	$41,000	$8,200	$8,200	$4,900
DEPLOYMENT	4,000	4,000	4,000	3,619[3]	2,500
OPERATION	200	200	200	200	100
MAINTENANCE	0	0	500[2]	500	500
TOTAL	$50,200	$45,200	$12,900	$12,519	$8,000

[1] compressor: $8,000
bubbler cannons: 10 @ $2,500
hardware, delivery and miscellaneous, $13,000

[2] estimated labour required for maintenance

[3] average cost over 5 yrs assuming 5% reduction/year

[4] all figures are estimates

Costs for two other systems tested at Thunder Bay are available for comparison with the air cannon bubbler system, and these are shown in Table 4.4. The air cannon system costs shown are for the system tested at Thunder Bay (Column A in Table 4.3). Column B shows costs for the rake bubbler system tested by V.B. Cook Co. Limited at the same time and in the same slip as the air cannon system [13], and column C shows costs for a line bubbler system tested at Thunder Bay in 1980 [14]. Both of these systems were prototypes and so are comparable with the air cannon system in terms of cost.

Table 4.5 also compares the annual cost of each system per unit area of ice melted, derived simply by dividing the cost by the area melted during the test. Areas melted by the 10-unit air cannon and the rake systems were measured accurately using air photographs. The 5-unit air cannon system was assumed to melt half as much as the 10-unit system. Area melted by the line bubbler is a rough approximation from a map in the diffuser test report [14]. Table 4.5 indicates that the 10-unit air cannon bubbler system was the most economical assuming a five year amortization period. On a one-year basis the rake system was more economical than the air cannon system because of the capital costs involved.

Tables 4.3 through 4.5 provide cost comparisons between two air cannon bubbler systems and two other types of bubbler systems. All were prototypes and all were used for only one season. The annual cost comparison assumed a 5-year ammortization period with no capital replacement and (except for the air cannon system) no annual maintenance costs other than deployment where necessary. With only one year's experience with these prototype systems, annual repair or refit costs could not be estimated. Previous reports suggest however, that the air cannon and rake systems will require little annual refit while the diffuser will need substantial repair or replacement due to damage from ships and from silting.

An additional and important consideration in evaluating bubbler systems is the system's ability to melt the required volume of ice in time for an April 1st opening of navigation. The cost of any of the bubbler systems tested could be very low in comprison with the cost of delayed shipping, and in this case the system with the highest probability of melting the required ice volume by April 1st would be the most economical. From this perspective, the air cannon bubbler system is the best choice.

TABLE 4.4

COST COMPARISON BETWEEN SYSTEMS

COST ITEM	A PROTOTYPE 10-UNIT [1] AIR CANNCN	B PROTOTYPE [1] RAKE	C PROTOTYPE [2] LINE
CAPITAL	$46,000	$5,400	$22,617
DEPLOYMENT	4,000	5,000	5,397
OPERATION	200		
MAINTENANCE	0		
TOTAL	$50,200	$10,400	$28,014
5-YEAR AMORTIZED ANNUAL COST	$13,400	$6,580	$9,920

[1] 1984 DOLLARS

[2] 1980 DOLLARS

TABLE 4.5

COST COMPARISON PER UNIT ICE CLEARED

SYSTEM	A PROTOTYPE 10-UNIT AIR CANNON	B 5-UNIT AIR CANNON	C PROTOTYPE RAKE	D PROTOTYPE LINE
ICE AREA CLEARED	2750 m^2	est. 1375 m^2	1100 m^2	n/a est.approx. 500 m^2
PROTOTYPE TOTAL COST	$18.25/$m^2$	$20.07/$m^2$ (est.)	$9.45/$m^2$	$56.02/$m^2$ (est.)
AMORTIZED ANNUAL COST	$4.88/$m^2$	$5.82/$m^2$	$5.98/$m^2$	$19.84/$m^2$

4.7 Summary of Advantages and Disadvantages

Tests in 1984 and reports from previous years show advantages and disadvantages related to installation and operation of each system. These are described in Table 4.6.

TABLE 4.6

SUMMARY OF ADVANTAGES AND DISADVANTAGES
OF CONVENTIONAL DIFFUSER AND AIR BUBBLER CANNONS

SYSTEM	ADVANTAGES	DISADVANTAGES
Conventional Bubbler	Capabilities known from theory	Area melted limited by plume velocity and diameter No control over direction or rate of horizontal flow Requires high air pressure Susceptible to damage from ships Difficult to remove from slip
Rake-type Diffuser	Location of melting can be controlled by moving diffuser. Relatively easy to retrieve and decommission at end of season	Requires frequent attendance for repositioning against ice edge No control over direction or rate of horizontal flow Requires high air pressure
Air Cannon Bubbler	Direction of horizontal flow can be controlled by deflector. Rate of flow can be controlled by bubble size or bubbler tube length Easy to remove at end of season. Low pressure air supply & low power consumption Pronounced wave action contributed to melting by overtopping ice. Can be designed to be built into the dock wall structure, and away from any ice or propeller action.	Must be removed at end of season or designed to be a part of the dock structure Higher capital cost than conventional bubblers

5. CONCLUSIONS

The tests at Thunder Bay Harbour in 1984 provided a study of the ice management capability and efficiency of the air cannon bubbler system. Operation of the air cannon system was monitored and its capabilities were compared with other systems. The following conclusions were drawn:

5.1 Horizontal Flow Development and Ice Suppression Mechanisms

Theory suggested that the air cannon design should produce an increased vertical flow over conventional bubblers, and theory plus laboratory tests indicated that an increased horizontal flow and improved ice suppression would result. Direct measurement of ice suppression of different air cannon deflectors was not possible during the field experiments, but visual observations of mechanisms of ice suppression agreed with laboratory results; generation of horizontal currents resulted in melting of the bottom surface of the ice cover at a distance from the bubbler hole.

Horizontal flow development was also shown by the water temperature measurements which indicated circulation of water 48 m distant from the nearest bubbler.

Three mechanisms of ice suppression were observed visually in association with the air cannon bubbler:

- melting of the bottom surface of the ice cover by horizontal currents
- melting of the bubbler hole edge, and
- melting of the top surface of the ice by wave overtopping.

The relative magnitude and efficiency of each mechanism was not measured.

5.2 Effect on Water Temperature and Thermal Reserve in Slip

The air cannon bubblers were highly effective at mixing a stratified water column. In both 1983 and 1984, initially stratified water columns were completely mixed by the air cannons within one day of operation. Some degree of horizontal mixing was also noted out to a distance of 48 m, although a uniform horizontal temperature was not achieved.

The effect of bubbling on the thermal reserve did not follow the theoretical model expected, either in 1983 or 1984. The thermal reserve available for melting the ice cover was expected to decline as warm water was circulated, and the heat was used to melt ice.

The available heat was theoretically sufficient to melt only 17% of the ice cover in 1984, and 10% in 1983. Measurements showed that a much larger volume of ice was melted in 1984 than could be explained by the thermal reserve available in the slip. In addition, the available thermal reserve increased in both 1983 and 1984, in bubbled and non-bubbled slips. This leads to two important conclusions. First, heat is added to elevator slips from some natural source prior to ice break-up at Thunder Bay Harbour. Second, the capability for ice suppression at Thunder Bay is not limited by the initial thermal reserve in the elevator slip.

5.3 Comparison of Systems

In terms of overall ice melting, the air cannon system melted ice at a mean rate of 193 m^2/day. This was more than twice as fast as a rake bubbler system operating in the same elevator slip. The air cannon system also melted the ice cover at a more constant rate than did the rake system.

The air cannon system was also more efficient than the rake system. First, the low pressure blower which was used to supply air to the air cannons consumed less power (20 HP) than the high pressure compressors (40 HP) required to supply air to the rake system. Second, the air cannon system required less frequent in-service maintenance than did the rake system.

Finally, the air cannon system was the most economical, when costs were amortized over a 5-year period.

6. RECOMMENDATIONS

The principal recommendation from this study is that "burper" type air cannon bubblers should be used to melt the ice cover in elevator slips at Thunder Bay Harbour.

In addition, the following studies should be undertaken to address the remaining questions in the design and operation of air cannon bubblers:

A. Air Cannon Bubbler Deployment Alternatives

Heavy equipment and divers are required to install the air cannon bubblers as they are presently configured. Once installed they cannot easily be moved to another site or adjusted to redirect the current as the ice edge melts back.

Studies should be undertaken to investigate alternative designs or deployment systems which would allow easier installation, re-deployment and removal of the bubbler system.

B. Study of Horizontal Flow Development

Development of a horizontal current under the ice cover is important to efficient bubbler operation. Previous studies showed that deflectors improve horizontal flow, but a study to compare the effectiveness of different deflectors was not successful due to equipment malfunction. This experiment should be repeated in 1985 with an improved instrument design.

C. Cost Comparison of Bubbler Systems

The cost comparisons in this report were necessarily crude, and included prototype development costs which might not be included in an operational system. Also, the operating conditions of each system were not identical.

More detailed cost comparisons should identify a standard or typical operating environment, select optimum efficient components and configurations for each system, and provide comparable cost estimates for purchase or construction, deployment and operation of each system.

D. Long Term Study of Water Temperatures in Slips at Thunder Bay

An important conclusion of the field tests was that heat is added to the slips during the period of air bubbler operation. The capability of ice suppression with air bubblers is therefore not limited by the initial heat content of the slip. This was shown during experiments in 1983 and 1984, but the general validity of the conclusion has not been studied. The source of heat may be present in only some slips or in only some years, depending on climatic conditions.

A multi-year study should be undertaken to monitor the natural temperatures of elevator slips at Thunder Bay Harbour. Such a study will help to assess the sources and variability of heat available for ice suppression using air bubblers or other methods.

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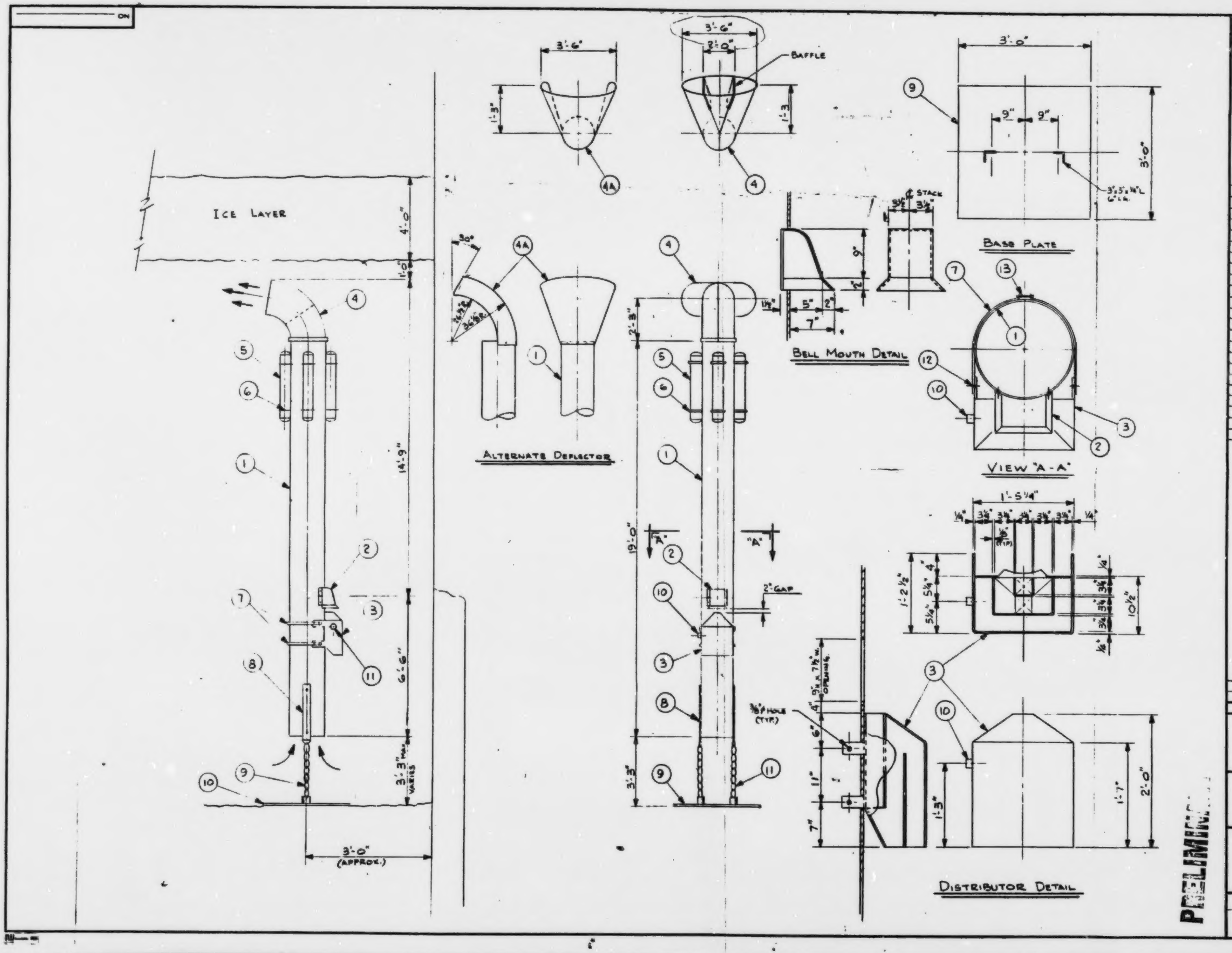
APPENDIX A

ATARA BUBBLER SPECIFICATIONS


ON
ICE LAYER
4'-0"
1'-0"
14'-9"
6'-6"
3'-3" MAX VARIES
3'-0" (APPROX.)
3'-6"
1'-3"
3'-6"
2'-0"
BAFFLE
1'-3
4A
4
30°
24¾"R.
36¾"R.
ALTERNATE DEFLECTOR
2'-3"
1½"
19'-0"
"A"
"A"
2" GAP
3'-3"
1
2
3
4
5
6
7
8
9
10
11
12
13
℄ STACK
3¼"
3¼"
9"
½"
5"
2"
7"
BELL MOUTH DETAIL
3'-0"
9"
9"
3'-0"
3"x3"x¼"L 6"LG.
BASE PLATE
VIEW "A-A"
1'-5¼"
¼"
3¼"
3¼"
3¼"
3¼"
3¼"
¼"
⅛" (TYP.)
1'-2½"
4"
5¼"
5¼"
½"
3¾"
3¾"
3¾"
10½"
½"
4"
9" x 7½" W. OPENING
⅜"Ø HOLE (TYP.)
6"
11"
7"
1'-3"
1'-7"
2'-0"
DISTRIBUTOR DETAIL

PRELIMINARY

NO.	DATE	DESCRIPTION OF REVISIONS	BY

PT	QTY.	DESCRIPTION
1	1	STACK PIPE 18"O.D. x 17½"I.D. x 19'LG.
		POLY ETHYLENE
2	1	BELL MOUTH ⅛" THK FRP
3	1	DISTRIBUTOR FRP
4	1	BUBBLE DEFLECTOR ⅛" THK FRP
5	8	FLOATATION CHAMBER
		3"Ø PIPE 3'-0" LG.
6	16	CHAMBER STRAP - 304 S/S
7	2	DISTRIBUTOR STRAP 304 S/S 2"W x 24"LG
8	2	LEGS - 2"W x 4'-0"LG x ¼"THK.
9	1	BASE PLATE 3'-0" x 3'-0" x ⅜" THK.
10	1	1"Ø SCREWED CONNECTION
11	2	CHAIN
12	4	MACHINE BOLT W/ NUT ½"Ø x 1"LG.
13	2	" " " ½" x 2" LG.

ABOVE QUANTITIES SHOWN
ARE FOR (1) ONE GUN ONLY
10 - REQ'D.

DWG NO.	TITLE

REFERENCE DRAWINGS

ATARA DE-ICING SYSTEM
THUNDER BAY ONTARIO
CANADA MALT DOCK
PROJECT NO. ____

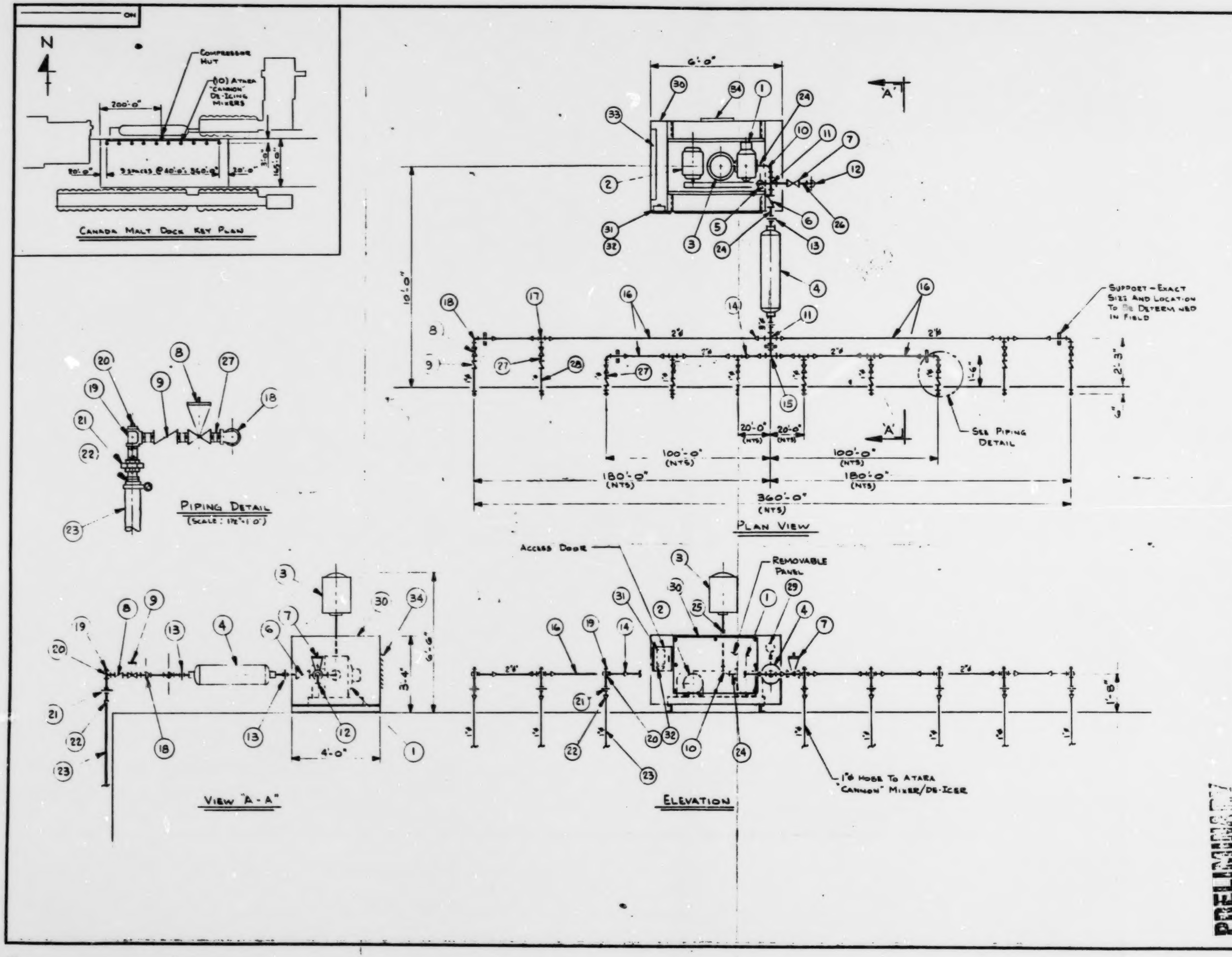
ATARA CORP

18"DIA. ATARA "CANNON"
MIXER / DE-ICING GUN

DRAWN	APPROVED	DATE	SCALE
P. GOLINO		30-01-84	

NO. 374-01-84

REV


N
Compressor Hut
(10) Atara "Cannon" De-Icing Mixers
200'-0"
20'-0"
9 spaces @ 40'-0" = 360'-0"
20'-0"
3'-0"
15'-0"
Canada Malt Dock Key Plan
6'-0"
'A'
10'-0"
Support - Exact Size and Location To Be Determined In Field
2'-3"
1'-6"
20'-0" (NTS)
20'-0" (NTS)
100'-0" (NTS)
100'-0" (NTS)
180'-0" (NTS)
180'-0" (NTS)
360'-0" (NTS)
See Piping Detail
Plan View
Piping Detail
(Scale: 1½" = 1'-0")
Access Door
Removable Panel
3'-4"
6'-6"
4'-0"
1'-8"
1" Hose To Atara "Cannon" Mixer/De-Icer
View "A-A"
Elevation

NO.	DATE	DESCRIPTION OF REVISIONS	BY

PT	QTY.	DESCRIPTION
1	1	Compressor - Fuller # GHV
		280 SCFM @ 11 PSIG c/w
		Base & Belt Drive Guard.
2	1	Motor - 1750 RPM 20 HP
3	1	Inlet Filter - Dollinger #
4	1	Discharge Silencer - 3"ø
		Universal # RD-3
5	1	Pressure Relief Valve
		2"×2" NPT
6	1	Check Valve - 3"ø Scr'd.
		150# Bronze - Jenkins Fig 54
7	1	Gate Valve - 2"ø Scr'd.
		150# Bronze Jenkins Fig 310
8	10	Gate Valve - 1"ø Scr'd.
		150# Bronze - Jenkins Fig. 310
9	10	Check Valve - 1"ø Scr'd.
		150# Bronze - Jenkins Fig. 54
10	2	3" × 90° Elbow - 150# M.I. Scr'd.
11	2	3"×3"×2"×2" Reducing Cross
		150# M.I. Scr'd.
12	3	2"× 90° Elbow - 150# M.I. Scr'd.
13	2	3" - Union - 150# M.I. Scr'd.
14	20	2"ø - Male Hose Fitting. T.o.e. c/w Clamp
15	1	3"×2"×2" - Red. Tee - 150# M.I. Scr'd.
16	*	2"ø - Multi-Purpose Hose · 2 Braid
17	6	2"×2"×1" - Red. Tee - 150# M.I. Scr'd.
18	4	2"×1"× 90° Red. Elbow - 150#, M.I. Scr'd.
19	10	1"×1"×1" - Tee 150# M.I. Scr'd.
20	10	1" - Plug - 150#, M.I., Scr'd.
21	10	1" - Union - 150#, M.I., Scr'd.
22	10	1"ø - Male Hose Fitting. T.o.e. c/w Clamp
23	*	1"ø - Multi-Purpose Hose · 2 Braid
24	9	3"ø × 6" Lg. Pipe Nipple · Sch 40 - T.B.E.
25	1	3"ø × 2'-0" Lg. Pipe Sch. 40 T.B.E.
26	4	2"ø × 6" Lg. Pipe Nipple · Sch. 40 - T.B.E.
27	26	1"ø × 6" Lg. Pipe Nipple · Sch 40 - T.B.E.
28	4	1"ø × 1'-8" Lg. Pipe · Sch 40 - T.B.E.
29	1	Pressure Gauge - ¼" Conn. 4½" Dial
		c/w Shut-off Valve
30	1	Compressor Hut 6'-0" × 4'-0" × 3'-0"
31	1	Motor Starter EMAC 1 Enclos.
		Six Contacts
32	1	3 Position Selector Switch
33	1	Space Heater
34	1	Hut Louvre 24" × 24"

DWG. NO.	TITLE

REFERENCE DRAWINGS

ATARA DE-ICING SYSTEM
THUNDER BAY ONTARIO
CANADA MALT DOCK
PROJECT NO.

ATARA CORP

COMPRESSOR PIPING
GENERAL ARRANGEMENT

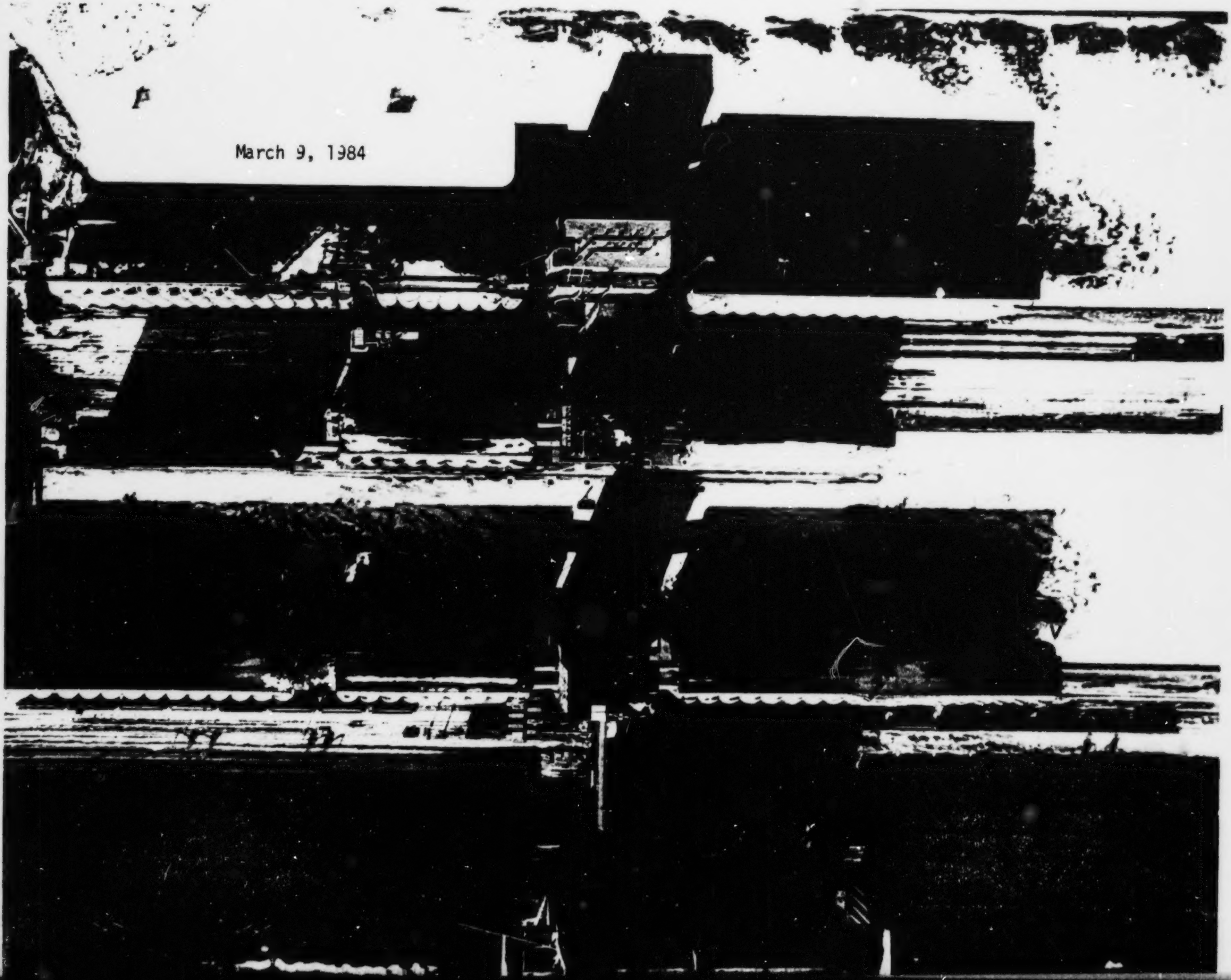
PRELIMINARY

DRAWN	APPROVED	DATE	SCALE
P. Golino		6/02/84	½" = 1'-0"

NO. 374-02-84
REV

APPENDIX B

AERIAL PHOTOGRAPHS



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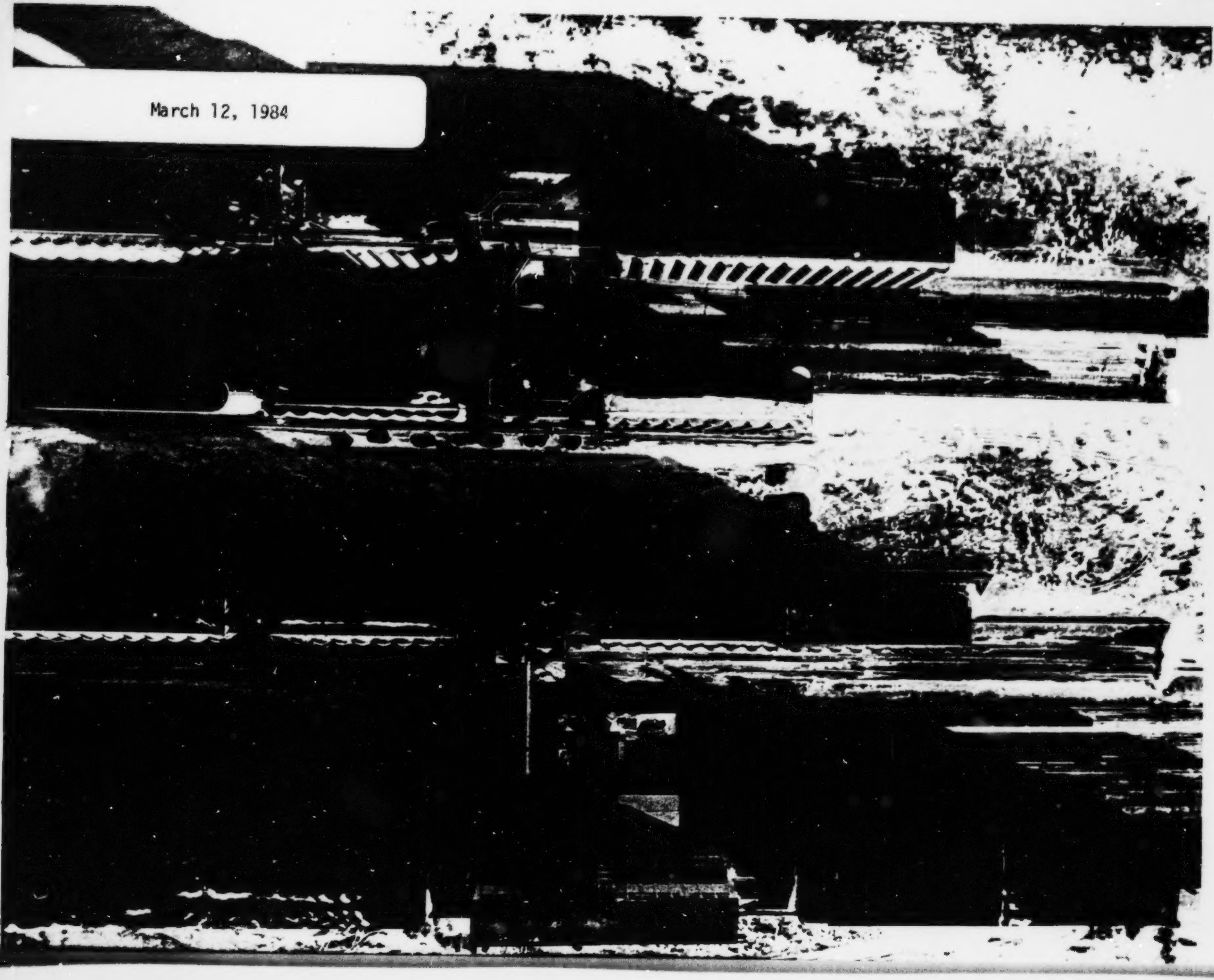

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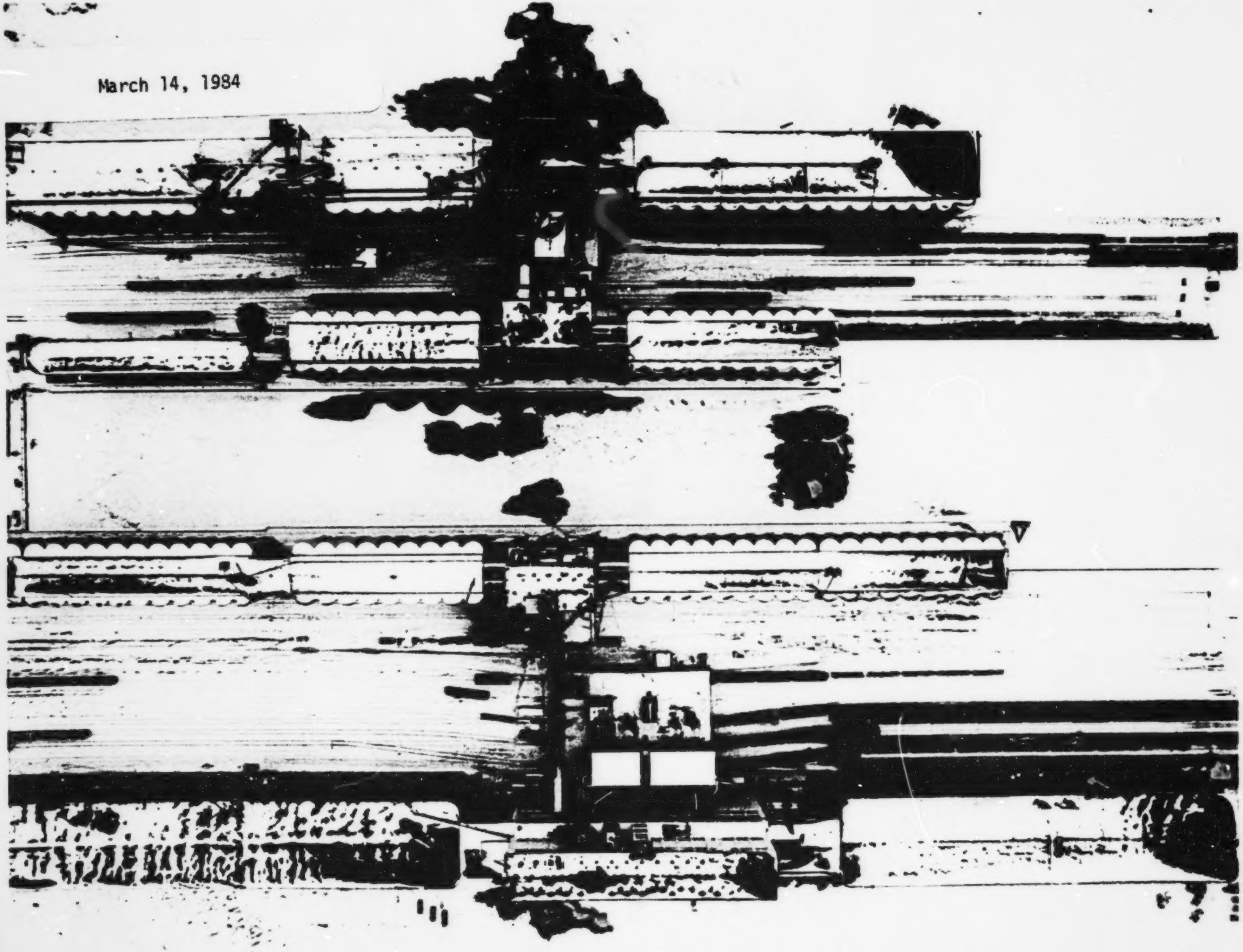

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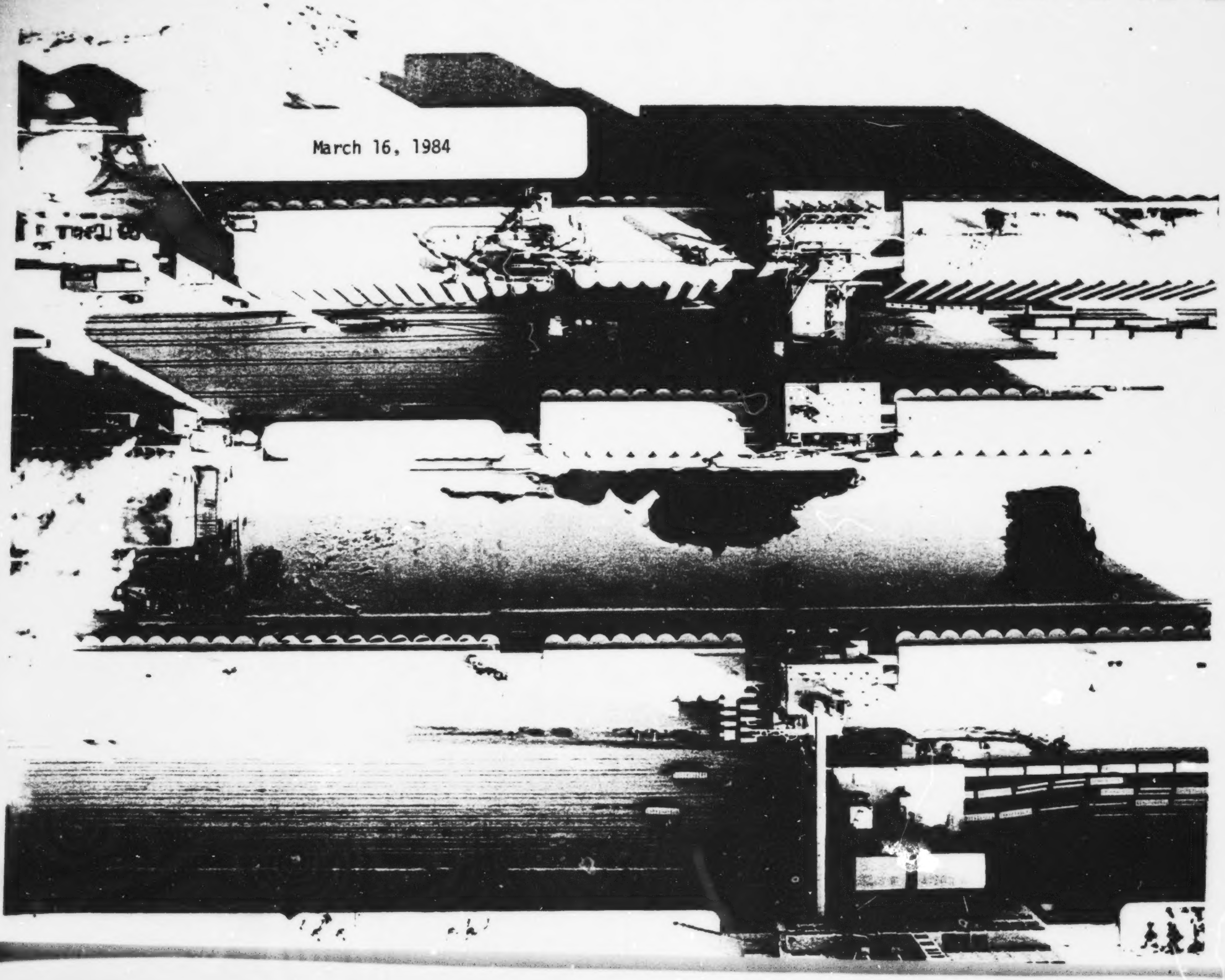

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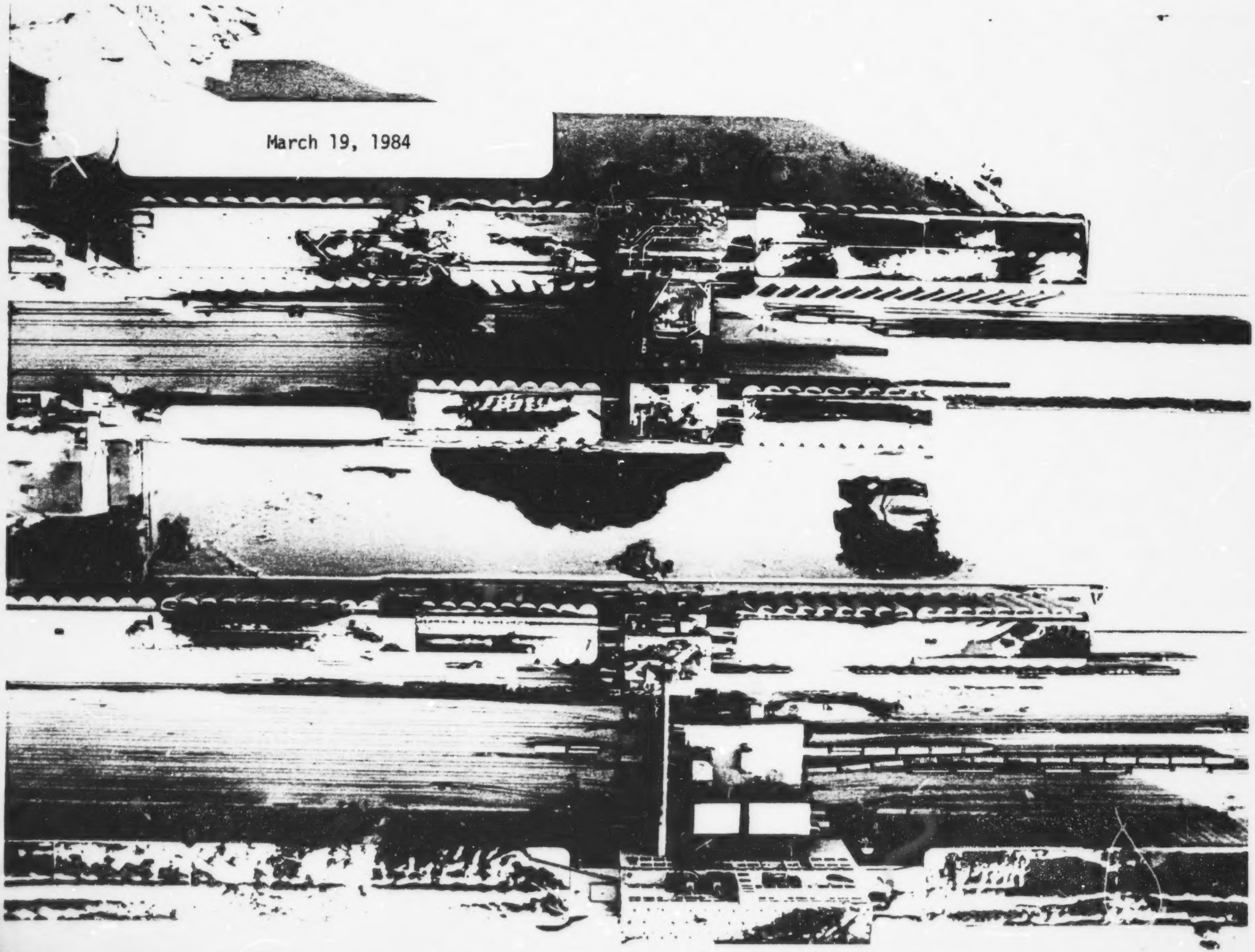

March 19, 1984

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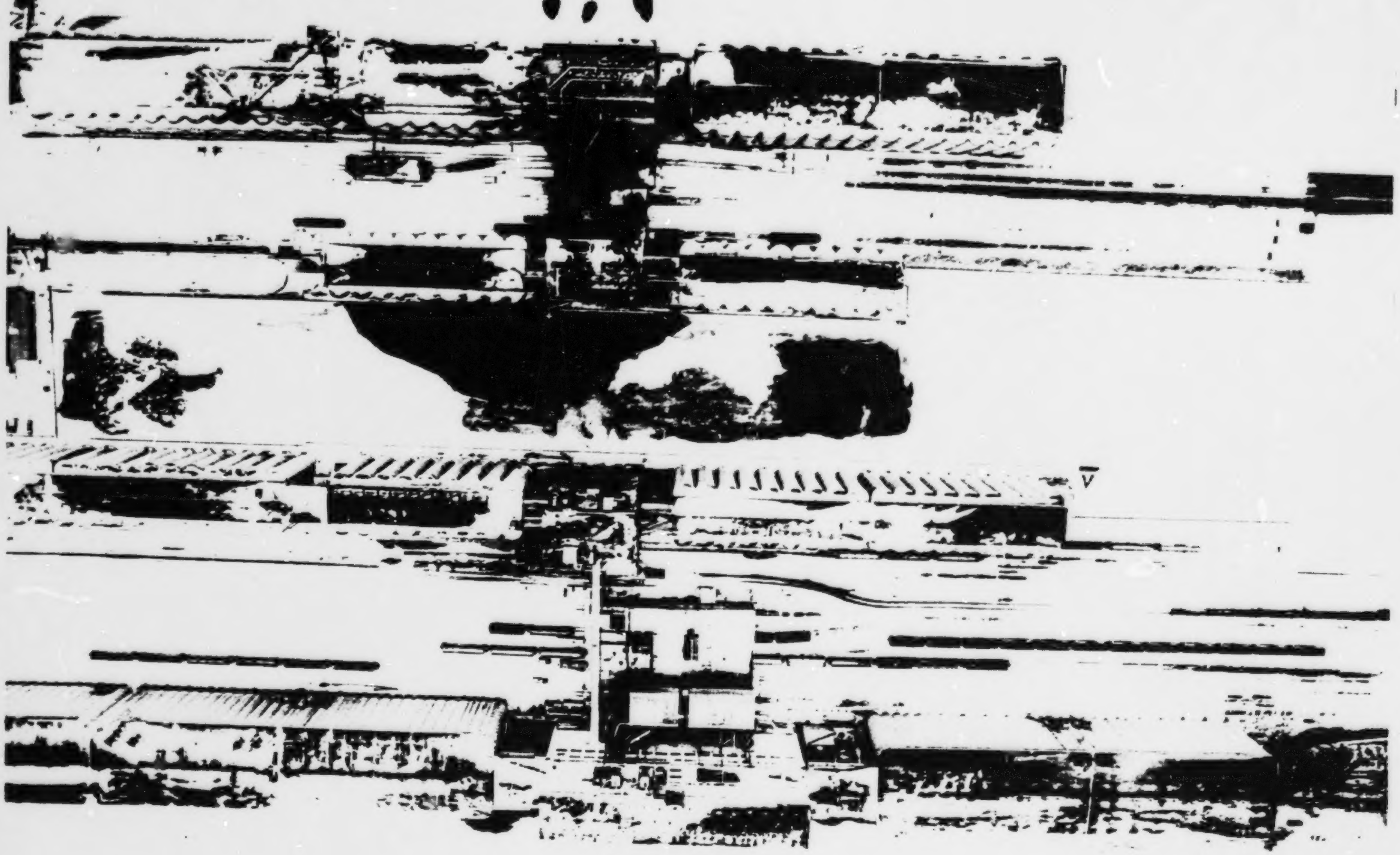

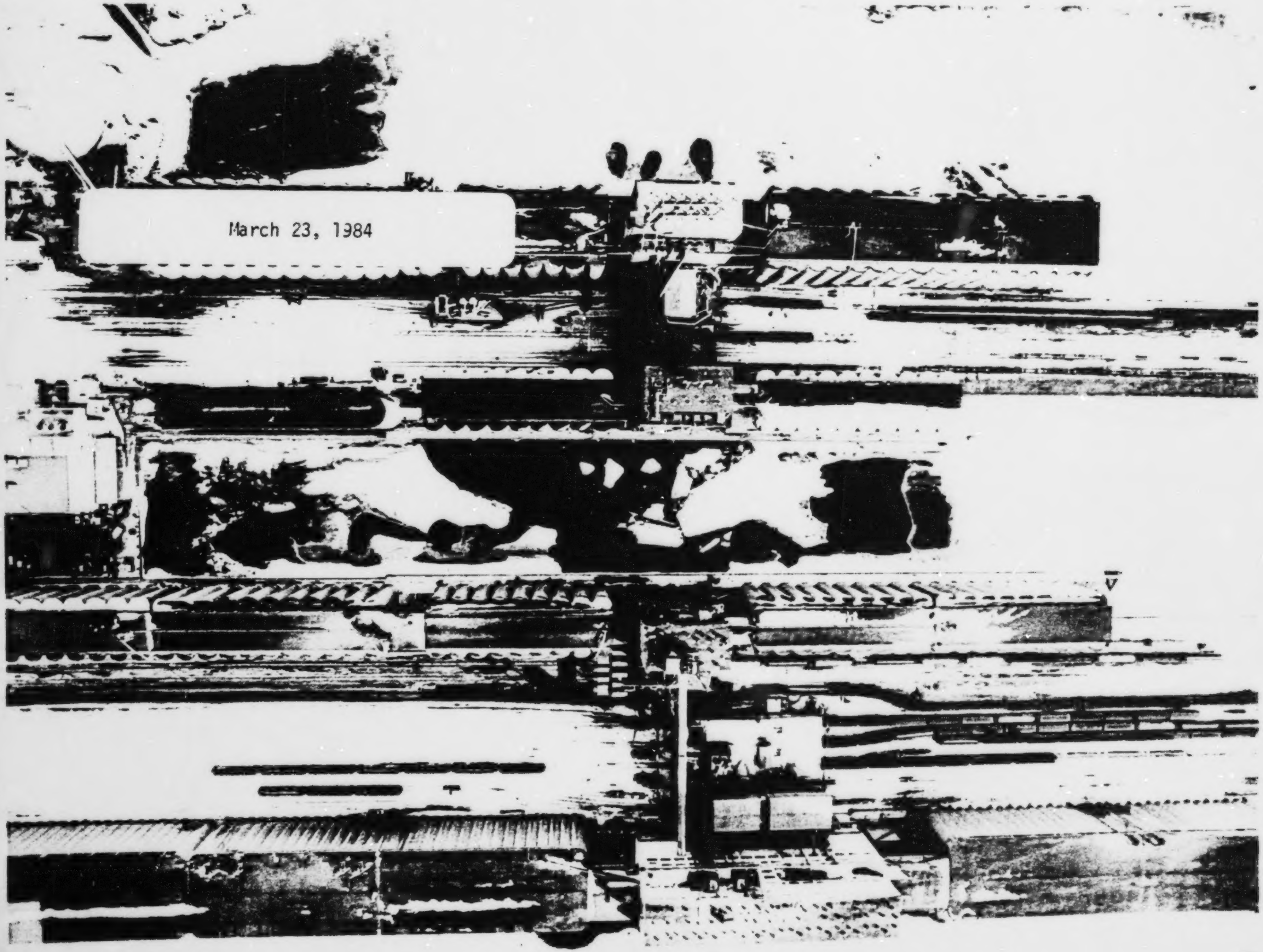

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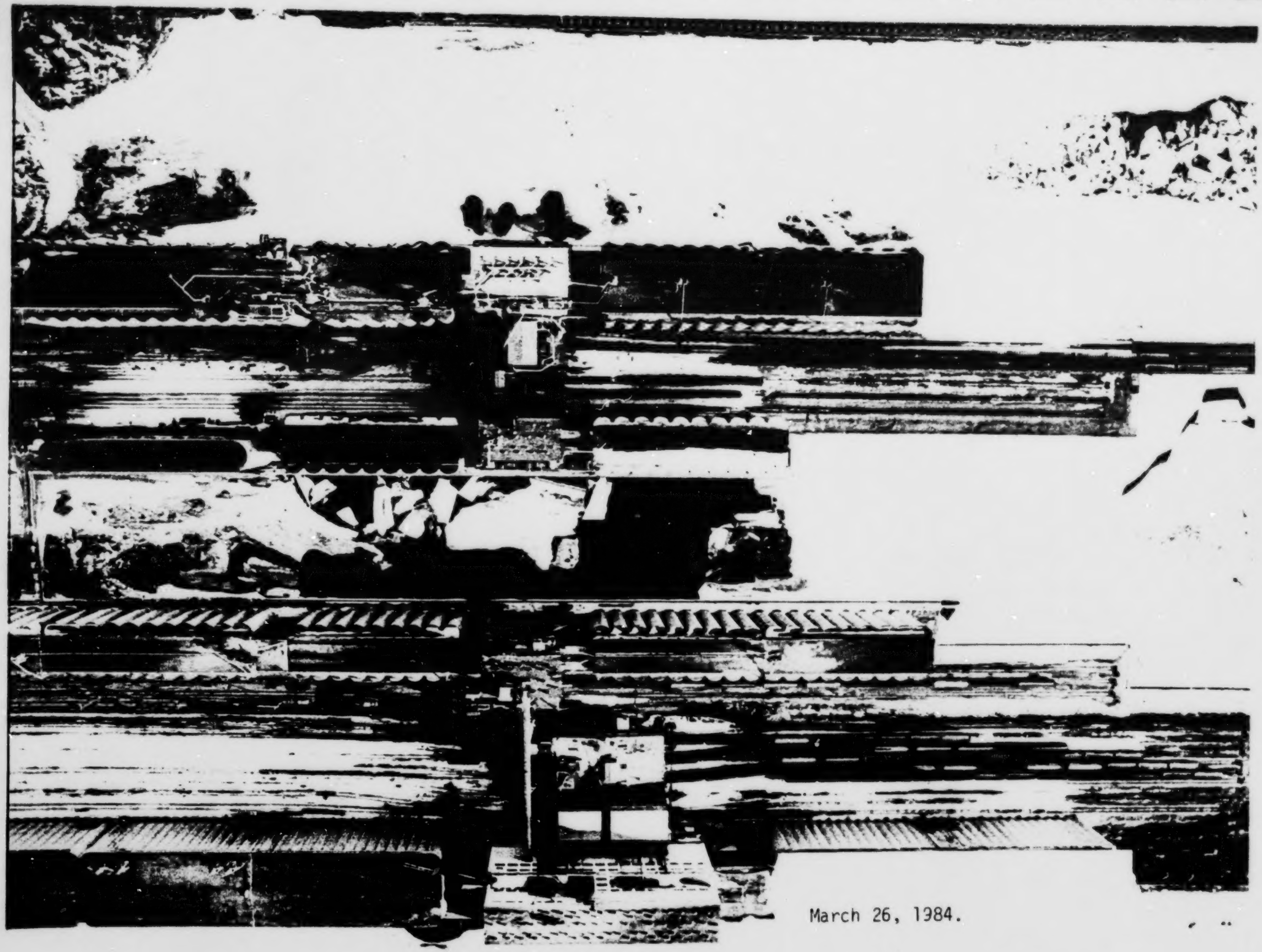

March 26, 1984.

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ARCTEC CANADA LIMITED

ARCTEC CANADA LIMITED FR1371C

TP 5835E

ICE MANAGEMENT IN THUNDER BAY HARBOUR WINTER 1984

VOLUME 11 - MANITOBA POOL #1 DOCK LOAD EXPERIMENT

PREPARED FOR:

TRANSPORTATION DEVELOPMENT CENTRE,
MONTREAL, QUEBEC.

SEPTEMBER 1984

BY

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D. HOWARD

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TP 5834E - July 1984

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R.S. Nishizaki

17. Abstract

A field experiment performed in March 1984 evaluating the feasibility of using an icebreaker to clear ice from elevator slips is described. These tests were performed in Thunder Bay Harbour using the CCGS ALEXANDER HENRY with and without an air cushion icebreaking bow (ACIB).

A slip located between two grain elevator structures was instrumented to measure loads induced in the ice field. Other measured parameters included building motion, ice and air temperatures, and ship position and velocity.

Ice forces measured using the ALEXANDER HENRY without the ACIB exceeded 184 kN/m (at which point the experiment was terminated). Maximum force measured using the ship and ACIB combination did not exceed 178 kN/m.

This study concludes that a conventional icebreaker should not be used to break an intact ice cover within the slip. The use of the ACIB attached to the ALEXANDER HENRY resulted in a significant reduction in ice loads and was shown to be effective for icebreaking within the slip.

18. Key Words
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17. Résumé

Ce rapport décrit les essais de déglaçage réalisés dans un bassin de chargement céréalier et mettant en oeuvre un brise-glace agissant seul ou couplé à une plate-forme à coussin d'air (PBCA). Ces essais ont eu lieu à Thunder Bay, en mars 1984, avec le brise-glace ALEXANDER HENRY.

Les parois d'un bassin de chargement, borné de chaque côté par un élévateur à grain, ont été instrumentées pour mesurer les forces exercées par les glaces au cours d'opérations de déglaçage. D'autres paramètres ont également été contrôlés, soit les mouvements des structures, la température de l'air et de la glace, ainsi que la position et la vitesse du brise-glace.

Les forces mesurées lorsque le ALEXANDER HENRY agissait seul ont dépassé 184 kN/m (valeur limite à laquelle il a été décidé de mettre un terme à l'expérience). Couplé à une plate-forme à coussin d'air, le brise-glace a induit une force maximum de 178 kN/m.

Il a été noté une baisse sensible des forces exercées par les glaces sur les parois du bassin lorsque le déglaçage était réalisé, efficacement d'ailleurs, par le tandem brise-glace/plate-forme à coussin d'air; d'où la conclusion que les brise-glace ne devraient jamais être utilisés seuls pour le déglaçage des bassins portuaires.

18. Mots-clés Maîtrise des glaces, déglaçage, ports quais, bassins portuaires, mélangeurs à canon pneumatique, essais	19. Diffusion Le CDT dispose d'un nombre limité d'exemplaires.

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1. INTRODUCTION

1.1 Background

Ice management systems have long been used by engineers to clear ice in northern waterways and harbours in most parts of the world.

A significant effort has been made by Transport Canada during recent years to investigate means of clearing ice-covered harbours. Several studies were carried out at Thunder Bay Harbour, the most northern harbour on the St. Lawrence Seaway. These projects included: the development of an air cushion icebreaking bow (ACIB), the installation of bubbler systems, the installation of a cannon bubbler developed by Atara Corporation, the measurement of water temperatures in various slips, the review of various ice management alternatives and the evaluation of ice management techniques.

Most of the earlier work in Thunder Bay concentrated these solutions to specific areas. For example, small confined areas were generally opened with the aid of bubblers or burpers, using the thermal reserve of the lake to melt the ice, whereas larger areas such as the harbour entrance were opened with the aid of an icebreaker with or without the ACIB. Rarely has an icebreaker been permitted to enter the small confined area of an elevator's slip while the ice is still intact. This restriction is mostly due to the elevator operators correctly being concerned that the additional iceloads applied by an icebreaker entering their slip could cause damage. Instead, the operators chose to use bubblers to initiate the ice clearing process, followed by a small icebreaking tug to break the remaining ice. This process required approximately two weeks of moderately warm weather followed by the availability of the tug before their slip could be opened.

1.2 Winter 1984 Experimental Program

The winter 1984 program consisted of two separate experiments, the first of these was an evaluation of a bubbler cannon for ice suppression, which is described in Volume I of this report. This volume, Volume II describes an experiment where an icebreaker was permitted to enter the slip between Manitoba Pool #1 and United Grain Growers (M) (UGGM) under controlled conditions. (Figure 1.1 shows a plan view of the area). While the icebreaker entered, the dock and grain elevator were instrumented to measure force and motion. These measurements were both recorded and displayed live in such a way that if any load or motion reached a predetermined level, the test could be aborted.

As a preliminary step, the slip between the Manitoba Pool #1 and UGGM was analysed in detail to calculate the maximum safe load that could be applied to the dock structure without causing damage. As well, a finite element model was used to predict the maximum load and acceleration the dock structure should experience when the icebreaker enters.

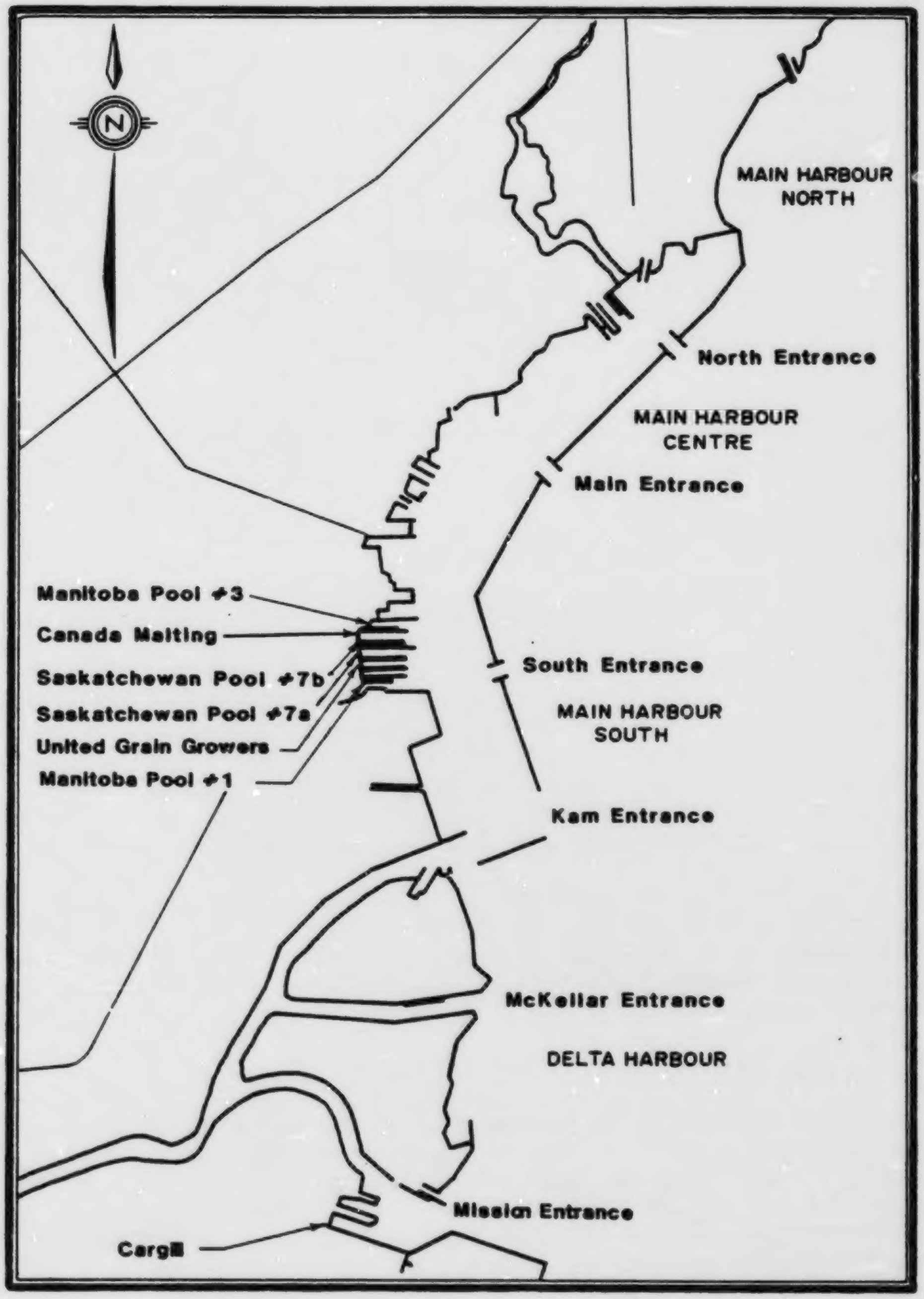
1.3 Objectives

The overall objectives of the ice management program are to extend the shipping season on the Great Lakes by eliminating the barriers which form in port loading berths and enable the harbour shipping season to open on the first of April every year.

This project measured the ice forces exerted on the dock, dock walls, foundations and the motion of the grain elevator caused by an icebreaking vessel working within the slip. A real time comparison of the allowable calculated forces with the measured forces ensured that the forces exerted did not exceed acceptable limits.

FIGURE 1.1

THUNDER BAY HARBOUR


N
MAIN HARBOUR NORTH
North Entrance
MAIN HARBOUR CENTRE
Main Entrance
Manitoba Pool #3
Canada Malting
Saskatchewan Pool #7b
Saskatchewan Pool #7a
United Grain Growers
Manitoba Pool #1
South Entrance
MAIN HARBOUR SOUTH
Kam Entrance
McKellar Entrance
DELTA HARBOUR
Mission Entrance
Cargill
0 .5 1 2 KM

2. CALCULATED LOAD MEASUREMENTS

2.1 Evaluation of Safe Dock Loads

V.B. Cook Company Limited of Thunder Bay was retained to analyse the dock foundation and calculate the maximum safe lateral load that the dock structure can withstand. Their report is reproduced in Appendix A with their summary given below.

> *The analysis of the UGGM and Manitoba Pool 1 structures has been completed. The revetment sheet piling is the critical structure element. The governing factor used to establish the maximum allowable lateral loads is the capacity of the dock system to support the upper end of the sheet piling.*
>
> *The maximum safe load, both perpendicular and parallel to the dock face, is 365 kN/m. Analysis indicates that the structures on both sides of the slip are similar in resistive capacities.*
>
> *The UGGM outshore dock is the most flexible structure in the slip system. The outshore annex dock of Manitoba Pool 1 is less flexible and the UGGM workhouse dock is the least flexible.*

2.2 Estimation of Dock Loads

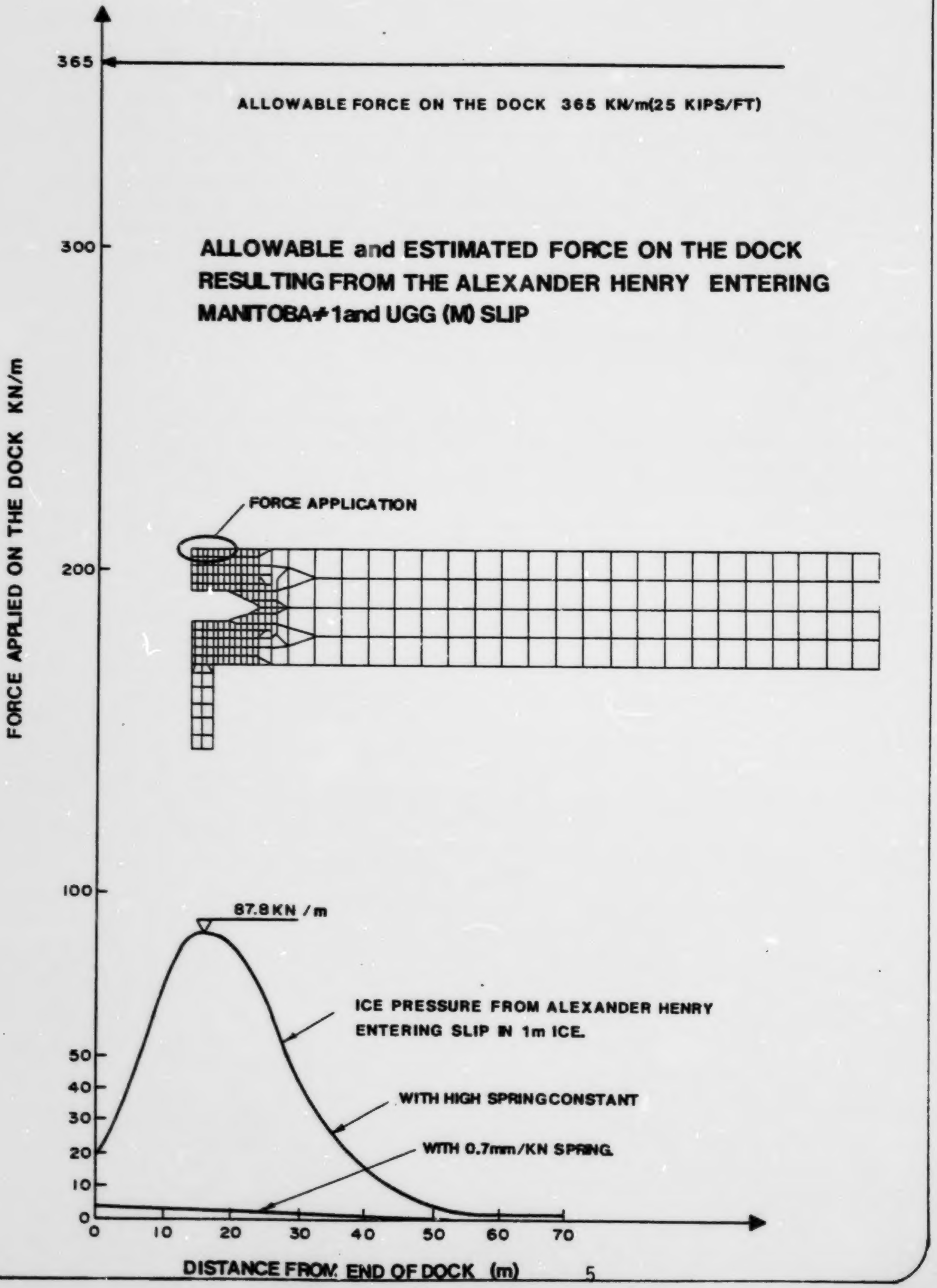
The estimation of forces applied to the dock during the penetration of the ALEXANDER HENRY were calculated using a finite element model. For this computer model, conservative approximations were made. Firstly, it was assumed that the ALEXANDER HENRY would enter the slip without the assistance of the ACIB. When the ACIB is used, the loads should be lower. Secondly, an ice thickness of 1 m was used in the math model when it was expected that the ice thickness would be about 0.75 m. Finally it was assumed that the dock would be infinitely rigid: a second scenario was taken giving the dock a spring constant of 0.7 mm/kN. The math model also assumed continuous icebreaking.

The results of the finite element analysis are summarized in Figure 2.1, with the details listed in Appendix B. The maximum dock load expected was 87.8 kN/m for an infinitely rigid structure and 3.0 kN/m using a spring constant of 0.7 mm/kN. It was expected that the measured leads should fall in this range.

2.3 Estimation of Grain Elevator Motion

The estimation of the building acceleration due to the impact of the ALEXANDER HENRY with nearby ice was performed using a finite element model. The problem was simplified by making the conservative approximation of the grain elevator. The worst case scenario used to estimate the maximum acceleration was that the ALEXANDER HENRY (or similar displacement ship) impact the corner of the dock at a speed of 5 knots. With this scenario, the maximum acceleration felt in the grain elevator would be 1.5 m/sec^2 or 0.15 g. The details of this calculation are given in Appendix C.

FIGURE 2.1



ALLOWABLE and ESTIMATED FORCE ON THE DOCK RESULTING FROM THE ALEXANDER HENRY ENTERING MANITOBA#1and UGG (M) SLIP

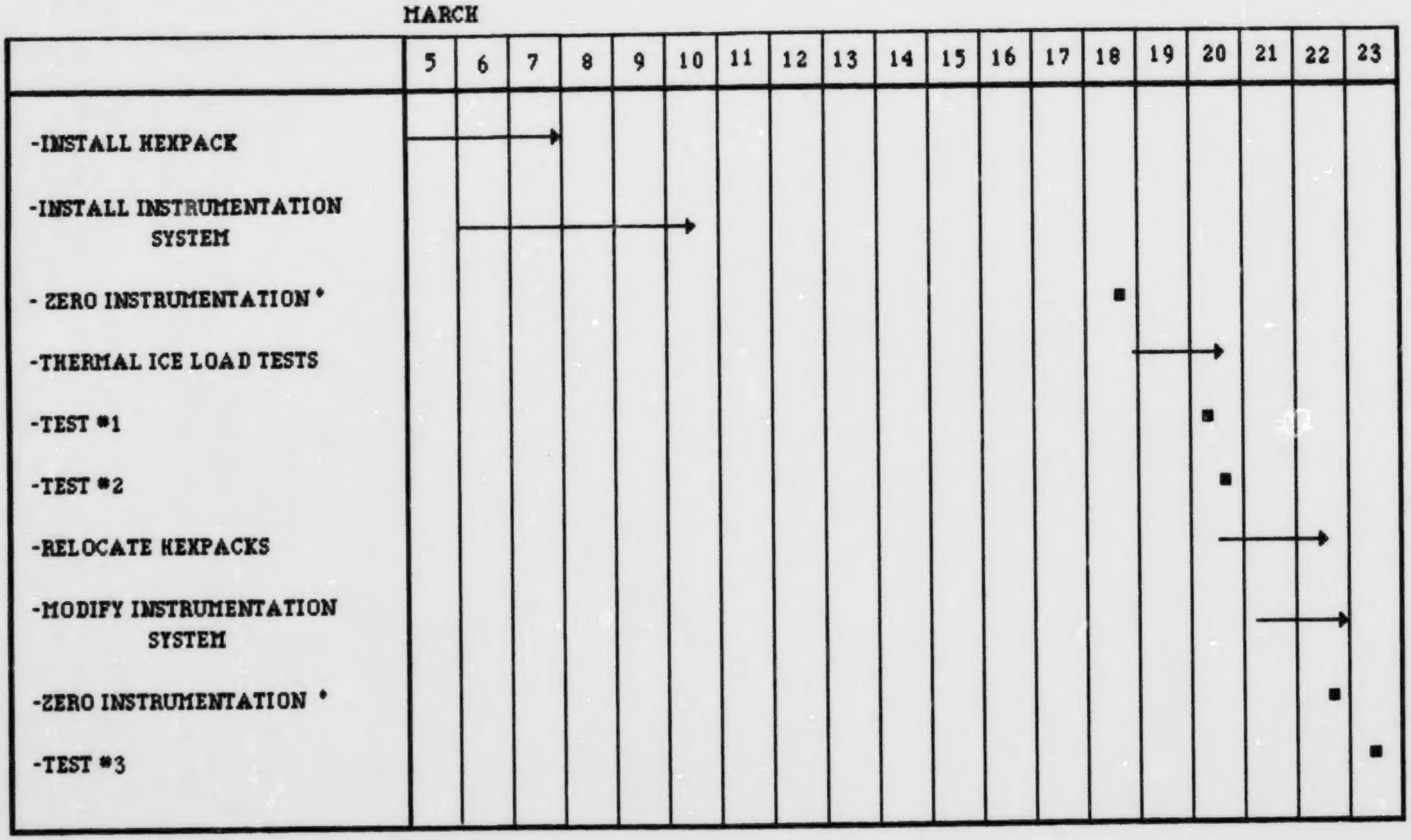
3. TEST SCHEDULE

The ice force measurement tests performed between the Manitoba Pool #1 and UGGM slips during the winter of 1983/84 have been divided into three primary tests and one secondary test. The first primary test occurred during the morning of March 20, 1984, when the CCGS ALEXANDER HENRY was brought within approximately 15 m of the entrance of the slip. At this point the threshold ice force level was reached and the test aborted. The second primary test occurred during the afternoon of March 20, 1984, when the CCGS ALEXANDER HENRY was coupled to the ACIB (Air Cushion Icebreaking Bow) and brought approximately 20 m into the slip. Following completion of the second test, four of the five Hexpacks were relocated to measure the distribution of ice loads along a greater length of the slip. With the Hexpacks and the instrumentation system modified, the third primary test occurred during the morning of March 23, 1984, when the CCGS ALEXANDER HENRY and the ACIB were brought 260 m into the slip. By the end of this test, 60% of the slip was broken free of ice.

The secondary test was performed between the night of March 18 and the morning of March 20, 1984 when ice forces due to thermal effects were measured. During this period both air and water temperatures were measured at another slip approximately 0.5 km from the Hexpacks [1].

Figure 3.1 outlines the schedule of events for the entire ice force measurement project.

FIGURE 3.1 TEST SCHEDULE



* The instrumentation system was zeroed before all three tests, however, these indicate additional times the instrumentation system was zeroed.

4. INSTRUMENTATION AND DATA COLLECTION

As outlined in Section 3, two independent instrumentation systems were used during this test program. The first instrumentation system was used to collect the thermal ice force data as well as all test data collected on March 20, 1984. The second instrumentation system was used to collect the data on March 23, 1984, following the relocation of the Hexpacks.

The transducer location for the first instrumentation system is shown in Figure 4.1, with a schematic of the data collection system shown in Figure 4.2. The five Hexpacks, two averaging and three segmented, were used to measure ice pressure. They were installed by cutting a slot in the ice in the positions shown in Figure 4.1, approximately 0.5 metres from the dock wall. The Hexpack was then lowered into this slot, carefully aligned to be vertical and parallel to the dock face, and frozen in place. Each Hexpack was lowered so that approximately 0.10 m protruded below the ice level. Therefore the segmented Hexpack would have the bottom three segments in ice with the top segment in air. Figure 4.3 shows how the Hexpacks were installed, and Appendix D lists the details of each Hexpack.

Two thermistor strings were frozen into the ice in the positions shown in Figure 4.1. Each string contained three thermistors with the first thermistor approximately 0.15 m from the bottom, the second in the middle and the third approximately 0.15 m from the top.

The accelerometer and video camera were mounted, as shown in Figure 4.1, at a height of approximately 35 m above the dock. The accelerometer was rigidly cemented to the concrete floor in the middle winch house. The accelerometer's sensitive axis was carefully aligned to be perpendicular to the dock.

The data collection system used for the first instrumentation system is shown in Figure 4.2. The fourteen Hexpack channels were conditioned with two series 2110 Vishay strain gauge conditioning racks. The accelerometer and Hexpack signals were recorded in parallel in both digital and analog form. The digital, real time data acquisition was controlled by an Apple II Plus. The Apple measured the 15 channels at a rate of 64 Hz per channel. Every eight measurements would be averaged and compared with the preceeding average for each channel. If there was a difference between these two averages, the Apple would save both the time and the value of the new average. If these two averages were equal, the Apple would disregard the new average. This process of saving only the values that changed conserved computer memory. When the computer's internal memory was full, the computer would momentarily pause to store all data on floppy discs. As well as acquiring data, the Apple system was used to display the non-zero corrected data so that the operator could abort the tests if any ice pressure surpassed a predetermined level.

As well as the Apple data acquisition system, an analog tape was recorded for all primary tests. The analog tape was recorded on a 28 channel, 5600 E Honeywell recorder. This tape record was later replayed and analyzed at Arctec Canada's Kanata Laboratory.

FIGURE 4.1 TRANSDUCER LOCATION for system #1

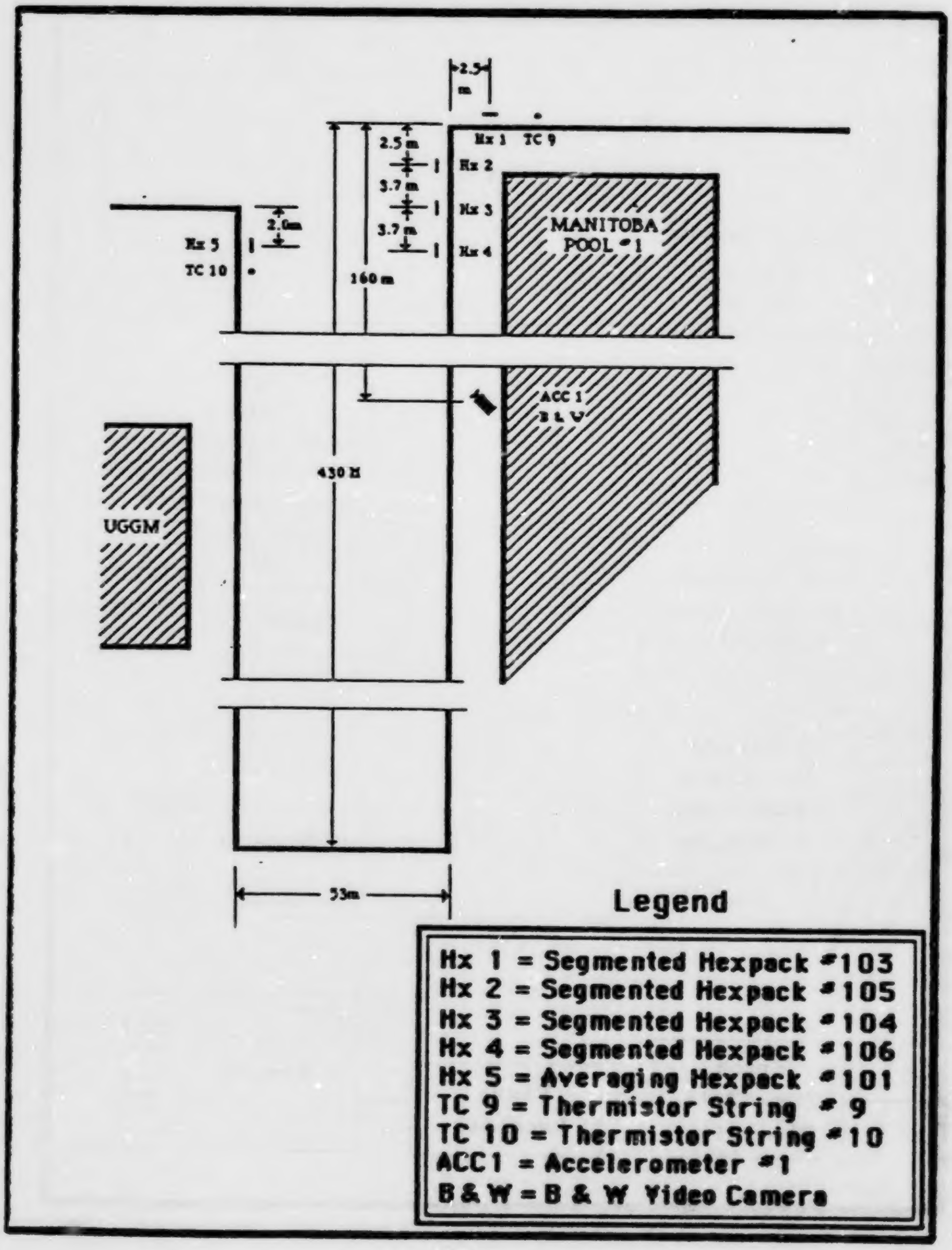

2.5 m
2.5 m
Hx 1
TC 9
Hx 2
3.7 m
Hx 3
3.7 m
Hx 4
2.0m
Hx 5
TC 10
160 m
MANITOBA POOL #1
ACC 1
B & W
430 M
UGGM
53m
Legend
Hx 1 = Segmented Hexpack #103
Hx 2 = Segmented Hexpack #105
Hx 3 = Segmented Hexpack #104
Hx 4 = Segmented Hexpack #106
Hx 5 = Averaging Hexpack #101
TC 9 = Thermistor String # 9
TC 10 = Thermistor String #10
ACC1 = Accelerometer #1
B & W = B & W Video Camera

FIGURE 4.2 DATA COLLECTION SYSTEM for system *1

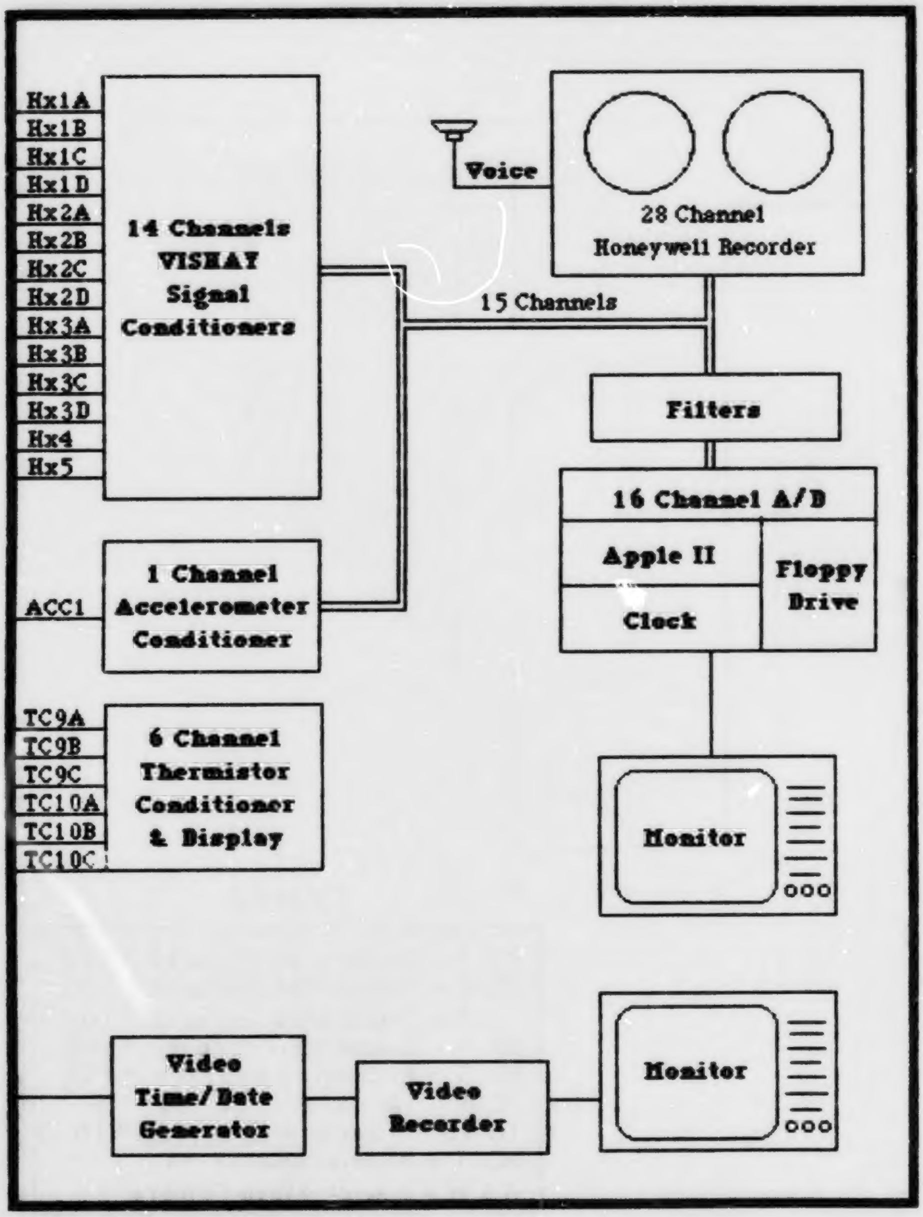
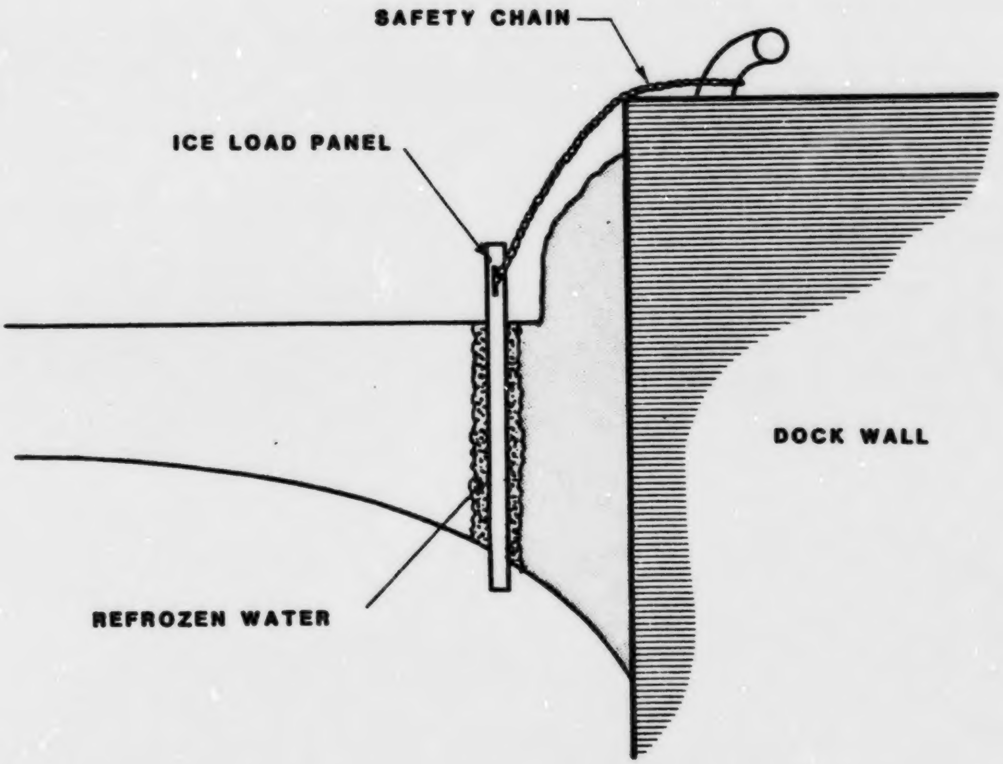

Hx1A
Hx1B
Hx1C
Hx1D
Hx2A
Hx2B
Hx2C
Hx2D
Hx3A
Hx3B
Hx3C
Hx3D
Hx4
Hx5
14 Channels VISHAY Signal Conditioners
Voice
28 Channel Honeywell Recorder
15 Channels
Filters
16 Channel A/D
Apple II
Clock
Floppy Drive
ACC1
1 Channel Accelerometer Conditioner
TC9A
TC9B
TC9C
TC10A
TC10B
TC10C
6 Channel Thermistor Conditioner & Display
Monitor
Video Time/Date Generator
Video Recorder
Monitor

FIGURE 4.3 PROFILE ICE LOAD PANEL INSTALLATION


SAFETY CHAIN
ICE LOAD PANEL
DOCK WALL
REFROZEN WATER

Also included in the data acquisition system were six channel thermistor conditioner and display and a black and white video system. The video system was operated continuously for all primary tests. The thermistor readings were recorded manually between March 19 and March 21.

The second instrumentation system was virtually the same as the first, with four of the five Hexpacks relocated. However with the Hexpacks moved, it was necessary to set up another instrumentation shack on the UGGM side of the slip. This permitted placing two Hexpacks on the UGGM side. As well, an additional accelerometer was added on the top floor of the UGGM workhouse. Figure 4.4 shows the positions of the relocated Hexpacks.

Instrumentation shack #2 remained unchanged with the exception of seven fewer data channels. Figure 4.5 shows the modified data collection system in shack #2. The data collection system for shack #3 contained one series 2110 Vishay strain gauge conditioning rack and one accelerometer conditioner. Due to time constraints, the wiring of the segmented Hexpacks was restricted to the bottom three segments. The top segment was above the ice line and would only measure a load if the ice had begun to pile up in front of the Hexpacks. Since the ice did not pile up during the first two tests, the top segment of the segmented Hexpack was not connected during test 3. Therefore only four Hexpack channels were recorded in shack #3; three channels from a segmented Hexpack and one from an averaging Hexpack.

As in shack 2, the data collected in shack #3 was recorded in analog form on an 8 channel SE recorder. However in shack #3, there was no digital data recording system. Instead, an Apple II was used to only measure and list the channel output.

FIGURE 4.4 TRANSDUCER LOCATION for system * 2

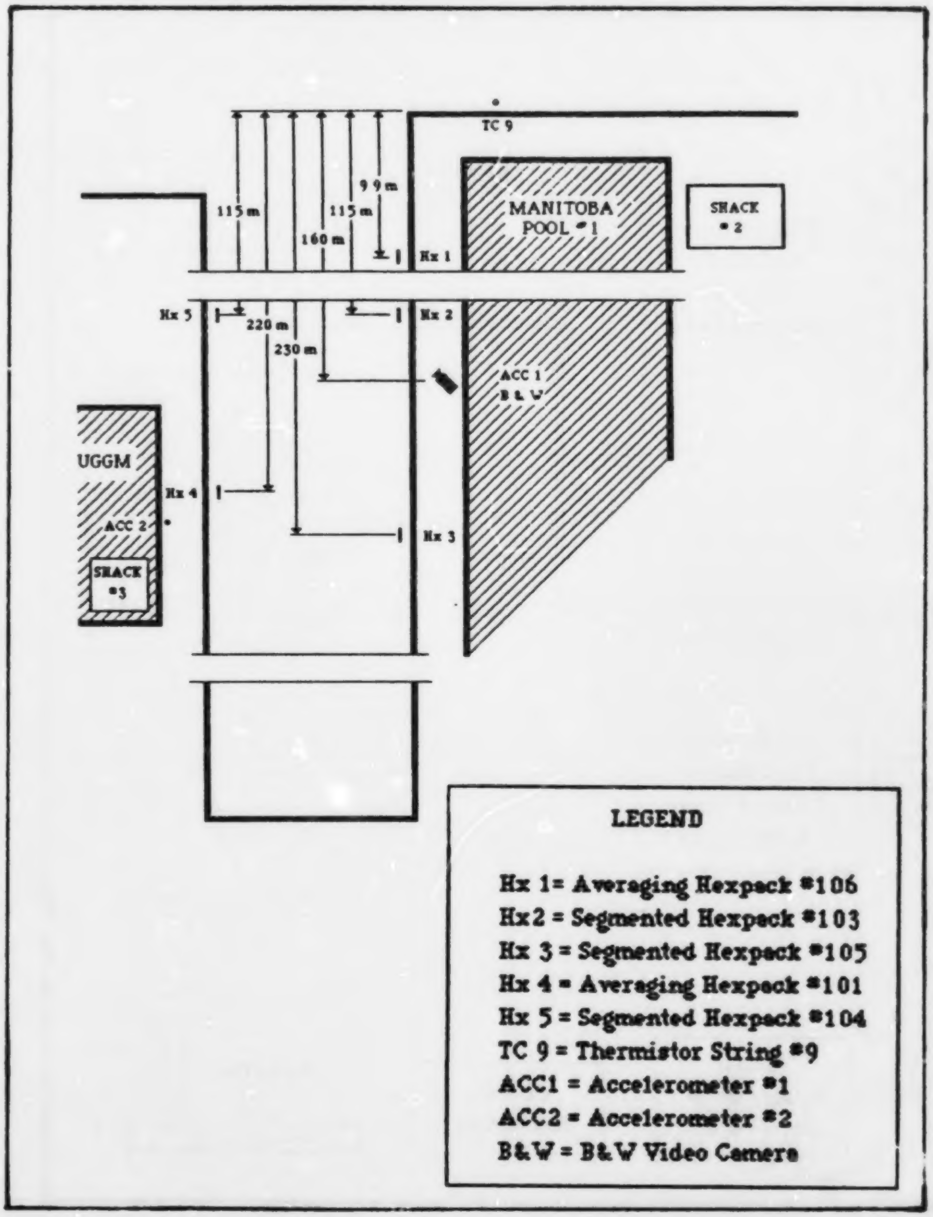

TC 9
9 9 m
115 m
115 m
160 m
Hx 1
MANITOBA POOL *1
SHACK *2
Hx 5
220 m
Hx 2
230 m
ACC 1
B & W
UGGM
Hx 4
ACC 2
Hx 3
SHACK *3
LEGEND
Hx 1= Averaging Hexpack *106
Hx2 = Segmented Hexpack *103
Hx 3 = Segmented Hexpack *105
Hx 4 = Averaging Hexpack *101
Hx 5 = Segmented Hexpack *104
TC 9 = Thermistor String *9
ACC1 = Accelerometer *1
ACC2 = Accelerometer *2
B&W = B&W Video Camera

FIGURE 4.5 DATA COLLECTION SYSTEM in shack #2 for system #2

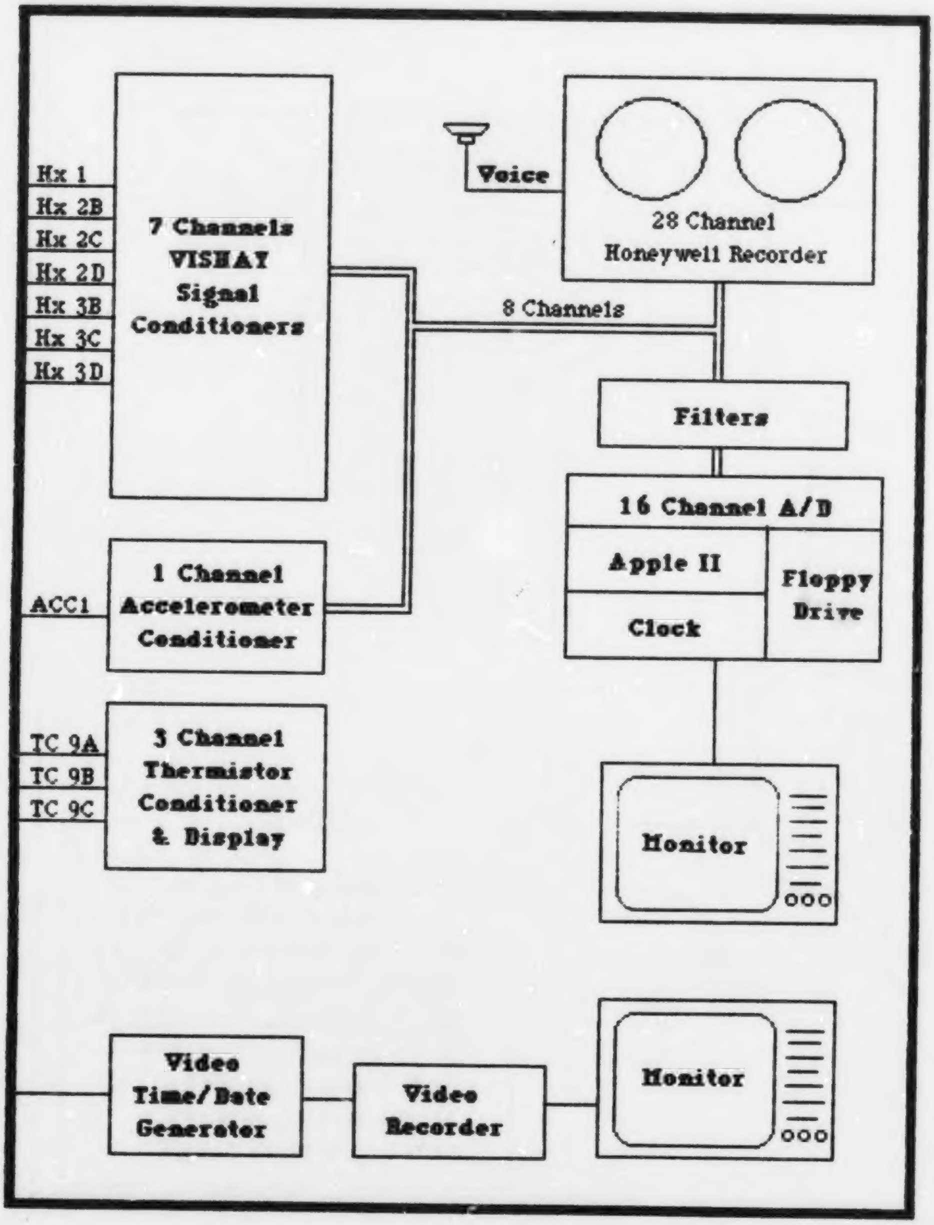
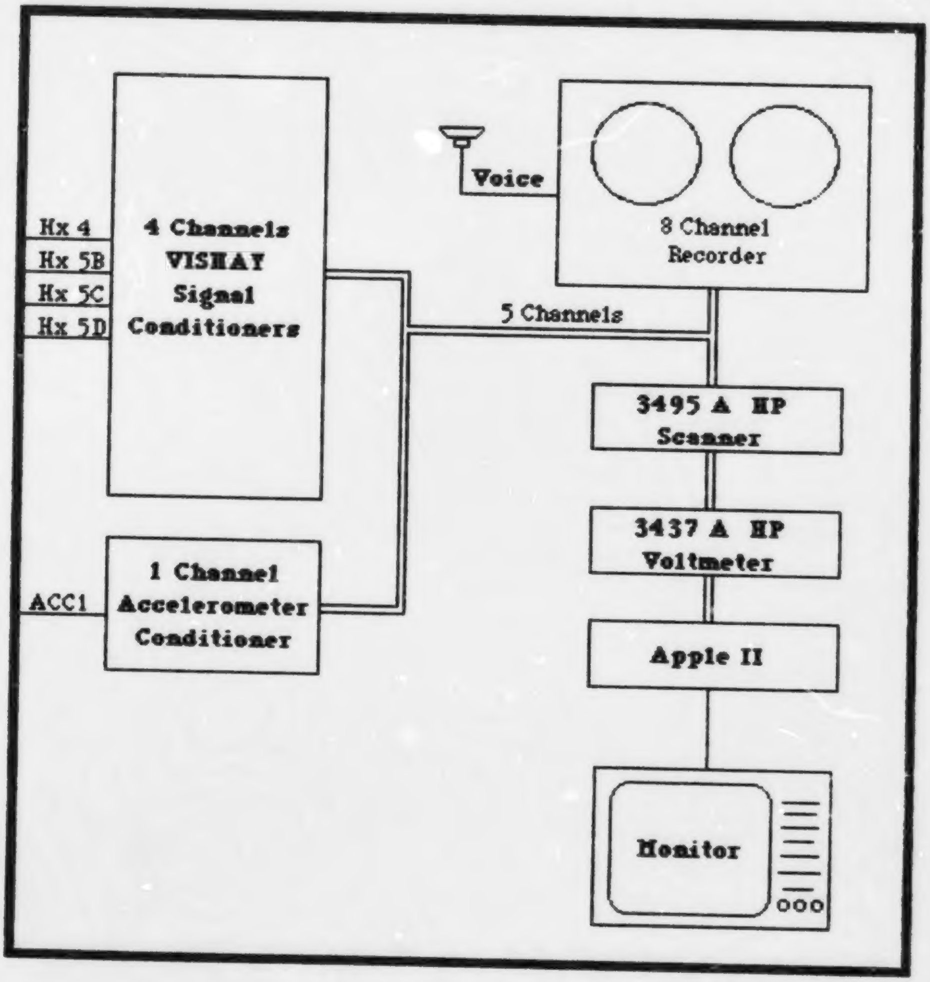

Hx 1
Hx 2B
Hx 2C
Hx 2D
Hx 3B
Hx 3C
Hx 3D
7 Channels VISHAY Signal Conditioners
Voice
28 Channel Honeywell Recorder
8 Channels
Filters
16 Channel A/D
Apple II
Clock
Floppy Drive
ACC1
1 Channel Accelerometer Conditioner
TC 9A
TC 9B
TC 9C
3 Channel Thermistor Conditioner & Display
Monitor
Video Time/Date Generator
Video Recorder
Monitor

FIGURE 4.6 DATA COLLECTION SYSTEM in shack #3 for system #2


Voice
8 Channel Recorder
Hx 4
Hx 5B
Hx 5C
Hx 5D
4 Channels VISHAY Signal Conditioners
5 Channels
3495 A HP Scanner
3437 A HP Voltmeter
ACC1
1 Channel Accelerometer Conditioner
Apple II
Monitor

5. ICE FORCE ANALYSIS

With the exception of a cursory analysis performed while acquiring the data, the entire data analysis procedure was performed at the Arctec Canada Laboratory in Kanata. The analysis procedure began with the data stored with the Apple. This data was primarily used to locate the time periods of ice load activity. Once located the periods of interest were replayed from analog tape on an O-graph chart recorder, where the quality of the data was assessed. The criteria used to assess the quality of the data is discussed in Section 5.1.

The better quality data was divided into approximately 2½ minute intervals and digitized using an HP9845B computer. The analog signal was filtered at 4 Hz using Butterworth bi-pole lowpass filters, and then digitized at 12 Hz.

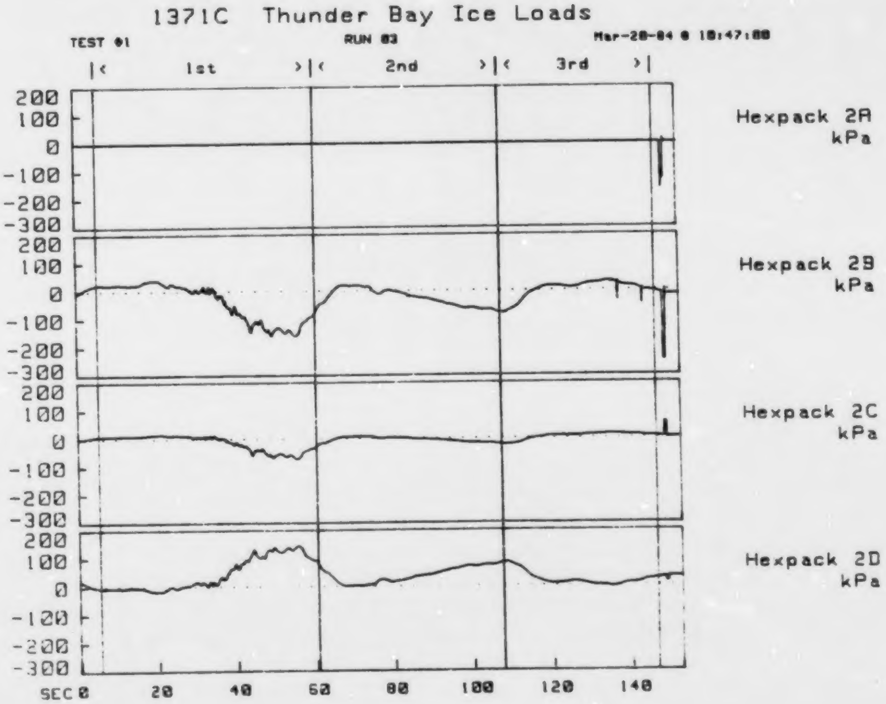
The Hexpacks measure pressure over all or portions (segments) of their surface areas. Average pressures on a Hexpack cannot be compared with pressures from a Hexpack segment because of the different surface areas involved. A more meaningful quantity is derived by converting these pressures to the horizontal dock load per metre of ice. The details of this conversion appear in Appendix E. Throughout this report the converted data has been termed the average load (e.g. Hex 1 average), derived by averaging the signals from each segment based on the percentage of their area. This must not be confused with a time average. This convention has been used for all five Hexpacks, including the nonsegmented version.

5.1 Quality Assessment

In assessing the quality of the analog data the following selection criteria were used. The first criterion considered was the effect of radio transmission on the data collected. Unfortunately, as the ice forces increased, so did the frequency of radio communictions, and thus virtually every period of interest has some form of radio interference. However, radio interference has a very distinctive pattern. Figure 5.1 shows a time series plot with a typical example of communication interference. Although varying in magnitude and sign, the radio interference at 148 seconds is shown as a distinct pulse in all channels. Although very distinctive to the eye, it is not feasible to perform a computer analysis without manually separating actual data from radio interference, and resulted in a slower analysis procedure.

The second quality criterion checked was the sensitivity range of each transducer. Before the tests began, calculations were made to predict the expected ice loads as well as building accelerations expected during these tests (see Section 2). These calculated values were used to set the gain of all transducers. The ice loads measured were actually higher than expected, whereas the accelerations were considerably lower. These higher ice loads resulted in a signal which exceeded the linear range of the analog recorders, and on occasion saturated the recorder. Tests in which this occurred will be identified. Since the range of the Apple's digital recording system is wider

FIGURE 5.1 SAMPLE TIME SERIES PLOT



than that of the analog system, the digital data could be substituted into the ice force analysis where necessary. Some Apple channels saturated during the collection of thermal ice stresses, however this problem was not encountered during testing. When an Apple channel saturates, adjacent channels are also affected. Therefore Apple data with any channel saturated has to be used cautiously.

Another point to mention is that during the tests on the morning of March 20th, the 0.9 km of wire connecting Hexpack 5 exhibited an intermittent break. Careful scrutinization of this Hexpack's output reveals that, apart from slightly more noise, the data is good when connected. However, when broken the signal saturated both the analog and digital recording systems. As discussed above, this does not affect the remainder of the analog channels, however, it does affect the other channels on the Apple system. For this reason, Hexpack 5 was disconnected for the second series of tests during the afternoon of March 20th. For the third series of tests on March 23 this problem was corrected.

Finally, for the data collected during the tests on March 23rd, the Hexpacks were not completely frozen in the ice following their relocation. Hexpacks which were moved, were able to measure compressive loads, but unable to measure more than a small tensile load.

5.2 Ice Load Measurements

The analog tape logs for each of the three series of tests are given in Tables 5.1 to 5.3. Included with this data is a brief description of the quality of the analog data. The data showing ice force activity is then subdivided into a maximum of 2½ minute long intervals in order to be processed. Table 5.4 summarizes the fourteen intervals that were processed. The remaining data either had no load (or constant load) or was of poorer quality due to points discussed in section 5.1 that no added information could be gained through its analysis.

The entire ice force analysis has been performed using an arbitrarily defined zero. Since thermal changes cause a considerable ice load, an absolute zero was not known. Therefore the measurements obtained are ice loads with respect to the arbitrarily selected zero. For all three tests, the arbitrarily selected zero was taken approximately five to ten minutes before the test started with the ALEXANDER HENRY well clear of the ice. Also included in Table 5.4 is the time when all zeros were taken.

Since the absolute zero was not known, all tests were scheduled to occur as early as possible in the morning when thermal ice loads would be lower [2]. For test #2, which was not possible to perform in the morning, the ice forces were monitored to ensure that there was not a significant change in the zero. Thermal ice loads will be discussed in more detail in Section 5.3.

Tables 5.5 to 5.12 summarize the results of test #1. Included in each summary table is the approximate location of the ALEXANDER HENRY as measured from the video.

TABLE 5.1

TAPE LOG OF TEST 1

DATE: MARCH 20, 1983
RECORDER: 5600 E

TAPE COUNT START	TAPE COUNT END	DESCRIPTION
169	182	Zeroing Channels
182.5	188.8	Bouncing at zero
188.8	196	Stable at zero
196	202.5	Impact
203	205	Communication Interference
205	212.5	Minor Impact
212.5	224.2	Impact
224.5	225.2	Communication Inferference
225.5	237.5	Impact
238	238	Communication Interference
238	256.8	Minor Load
256.8	258	Communication Interference
258	261.8	Minor Load
261.8	262.4	Communication Interference
262.4	268.3	Minor Load
268.3	276.1	Communication Interference
276.1	349	Stable at a minor load
349	374	Impact
374	380	Periodic Communications over stable load
380	386	Impact
386	412.5	Periodic Communications over stable load
412.5	440.5	Stable at Load
440.5	448.8	Communication Interference
448.8	459	Stable at Load
	459	End of Test

TABLE 5.2

TAPE LOG OF TEST 2

DATE: MARCH 20/84
RECORDER: 5600 E

TAPE COUNT START	TAPE COUNT END	DESCRIPTION
576.8	579.3	Zeroing channels
579.3	589	Bouncing zero
589	590	Communication Interference
590	604	Bouncing zero
604	612.5	Periodic Communication over Bouncing zero
612.5	632	Periodic Communication over Impact
632	680.7	Stable at load
680.7	688.2	Periodic Communication over stable load
688.2	709.8	Periodic Communication over bouncing load
709.8	746	Stable at Load
	746	End of Test

TABLE 5.3

TAPE LOG OF TEST 3

DATE: MARCH 23/84
RECORDER: BOTH 5600 E AND S.E.

5600 E TAPE COUNT START	5600 E TAPE COUNT END	S.E. TAPE COUNT START	S.E. TAPE COUNT END	DESCRIPTION
757	758	-	-	Zeroing Hexpacks 1, 2 and 3
-	-	4.0	14.0	Zeroing Hexpacks 4 and 5
758	768	-	15.5	Bouncing Zero
768	774.3	15.5	19.0	Communications over bouncing zero
774.3	783.0	19.0	24.0	Bouncing Zero
783.0	831.8	24.0	51.6	Periodic Communication over bouncing zero
831.8	855.9	51.6	65.3	Periodic Communication over impact
855.9	862.0	65.3	68.8	Peroodic Communication over bouncing load
862.0	874	68.8	75.6	Periodic Communication over impact
874	885	75.6	81.8	Periodic Communication over bouncing load
885	879	81.8	88.6	Periodic Communication over impact
897	1021	88.6	130	Periodic Communication over bouncing zero
	1021		130	End of test

Figures 5.2 to 5.9 show the results of Test #1. Drawn with each Hexpack is the maximum ice force vector measured during the entire 2½ minute long interval. Although the maximum ice load measured by each Hexpack occurred at slightly different times, generally they occurred within a few seconds of each other. Superimposed on these figures is the approximate position of the ship. Shown as a dotted line is the maximum dock load derived by interpolating and extrapolating from the measured results.

As shown in Tables 5.5 to 5.12, the ice forces measured by all five Hexpacks vary widely. Hexpack 1, which is located on the end of the dock, never exceeds a load of 15 kN/m during icebreaking beyond the slip. However during this same time the Hexpacks in the slip reached a considerable load. Hexpacks 2, 3 and 4, which are within a span of 7.4 m, vary by as much as 62.41 kN/m. With the exception of runs 2 and 8, the farther the measurement is taken away from the end of the dock the higher the load. This is to be expected since the lengths of the Manitoba Pool #1 and UGGM piers are not equal. As a pressure is produced in the intact ice sheet, (either by thermal effects or by a ship) the ice load closer to the end of the Manitoba Pool dock will not be as constrained as the loads farther along. This is due to the rigidity of the opposing dock being considerably higher than the rigidity of the unconstrained ice. It was expected that by placing the three Hexpacks in this manner the peak force would be seen on either Hexpack 2 or 3 and that the load measured with Hexpack 4 would have been lower. However it appears that the peak force occurs past Hexpack 4. Therefore, the value of the peak force is not known. However due to a stress concentration near Hexpack 5, it is expected that the peak force seen on the Manitoba Pool #1 side would be lower than the value measured by Hexpack 5.

Although the location of Hexpack 5 is opposite to Hexpack 4, the ice load measurements are considerably higher. On average the ice loads measured with Hexpack 5 are 2.61 times larger than Hexpack 4. The reason for this is the unequal lengths of the two docks. As discussed above, the ice loads closer to the end of the Manitoba Pool are not as constrained as the loads farther along the dock. However these ice loads must have a reaction if the ice is to remain stationary. Consequently the ice load measured by Hexpack 5 is larger due to a smaller reaction area. Figures 5.2 to 5.9 show schematic representations of the ice loading parallel to the dock face caused by pressure applied by the icebreaker in the harbour. With the exception of a small amount of shear reaction across the end of the UGGM dock, the areas under the load distribution curves should be equal. Therefore, the loads measured at the end of the UGGM dock must be considerably larger than the loads measured along the same length of the Manitoba Pool #1 dock.

In general, as the ALEXANDER HENRY got closer to the dock the ice loads increased. The highest ice load measured during test 1 occurred on the UGGM side and measured 183.49 kN/m. The highest measurement on the Manitoba Pool #1 side occurred at approximately the same time on Hexpack 4 and measured 74.76 kN/m. Since the ALEXANDER HENRY was not permitted to enter the slip during test 1, these ice forces would be equivalent to what the dock would regularly see while the harbour is being opened.

TABLE 5.4

SCANNED DATA SUMMARY

TEST #	RUN #	DATE	TIME	5600 RECORDER TAPE COUNT START	5600 RECORDER TAPE COUNT END	S.E. RECORDER TAPE COUNT START	S.E. RECORDER TAPE COUNT END	COMMENT
ZERO	01	MARCH 20	10:40:32	182	188	-	-	
1	01	"	10:43:34	196	203	-	-	
1	02	"	10:45:30	205	212	-	-	
1	03	"	10:47:00	212	224	-	-	
1	04	"	10;49;54	225.5	237.5	-	-	
1	05	"	10:53:26	242	253	-	-	
1	06	"	11:16:22	349	361	-	-	
1	07	"	11:18:56	361	373.5	-	-	
1	08	"	11:23:07	380.5	386	-	-	
ZERO	02	"	14:56:30	581	589	-	-	
2	01	"	15:02:44	610	622	-	-	Periodic Communication
2	02	"	15:05:19	622	632	-	-	Periodic Communication
ZERO	03	MARCH 23	10:31:06	758	761	16	17.7	
3	01	"	10:46:29	830	842	50.6	57.4	Periodic Communication
3	02	"	10:49:03	842	854	57.4	64.2	Periodic Communication
3	03	"	10:53:20	862	874	68.7	75.6	Periodic Communication
3	04	"	10:58:16	885	897	81.8	88.6	Periodic Communication

TABLE 5.5

THUNDER BAY ICE LOAD TEST SUMMARY

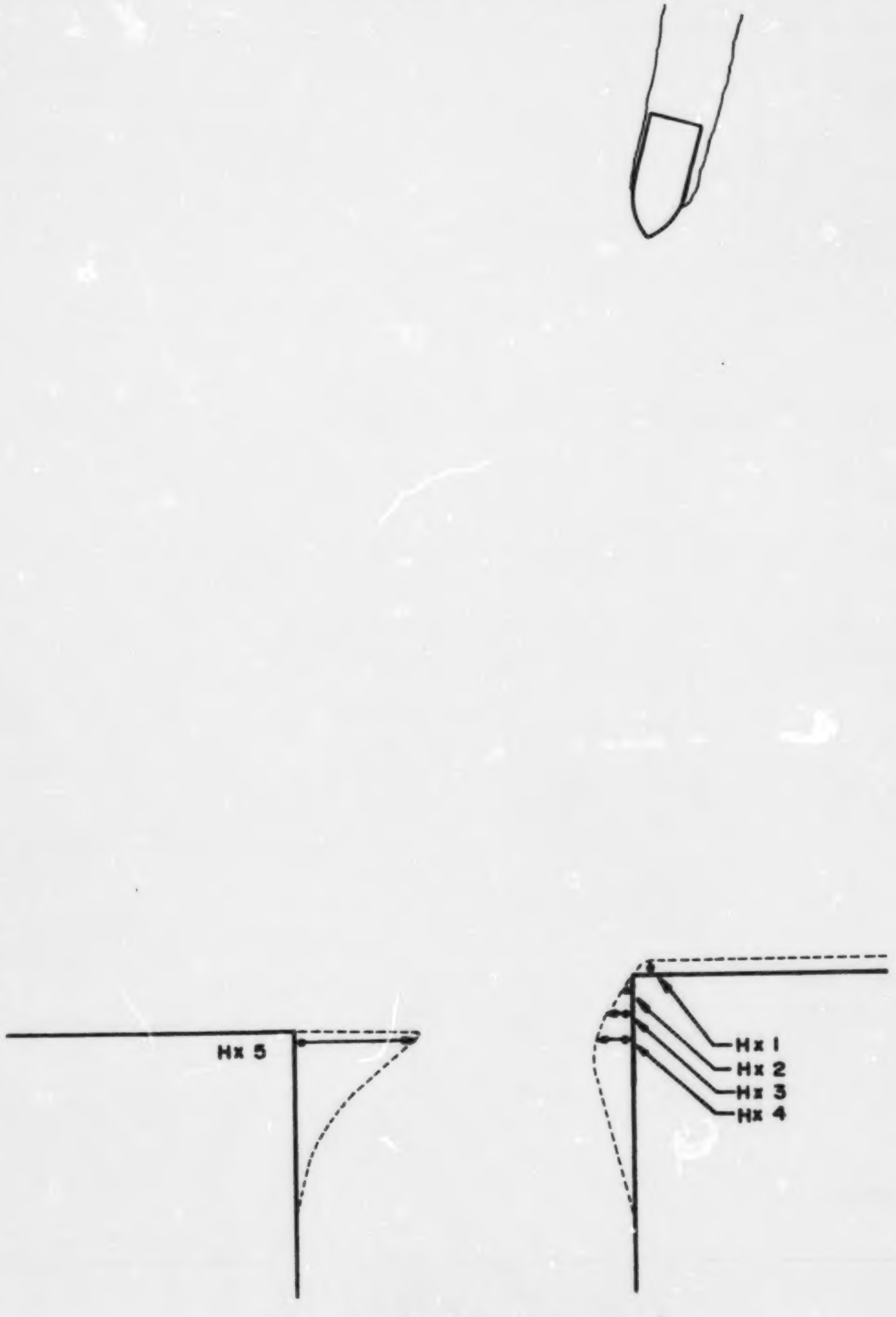
Test #: 1
Run #: 01
Date: Mar-20-84
Scan Begins at: 10:43:34
Duration of Scan: 90 sec
Scan ends at: 10:45:04
Type of test: Alexander Henry
Location of Ship: 120 m E-S-E of dock
Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	0.87	-0.58	kPa
Hex 1B	0.60	-4.41	kPa
Hex 1C	40.76	-60.91	kPa
Hex 1D	55.89	0.82	kPa
Hex 2A	0.72	-1.12	kPa
Hex 2B	23.19	-140.57	kPa
Hex 2C	8.28	-58.32	kPa
Hex 2D	123.16	-12.87	kPa
Hex 3A	1.21	-1.20	kPa
Hex 3B	36.57	-337.71	kPa
Hex 3C	33.30	-1.46	kPa
Hex 3D	177.31	-1.97	kPa
Hex 4	13.61	-2.70	kPa
Hex 5	64.12	-28.49	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	12.03	-6.78	kN/m
Hex 2 aver	5.89	-21.17	kN/m
Hex 3 aver	18.40	-60.16	kN/m
Hex 4 aver	27.23	-5.40	kN/m
Hex 5 aver	96.18	-42.73	kN/m

Comments: Two communication spikes after 80 sec.

FIGURE 5.2

DOCK LOAD DISTRIBUTION
TEST I RUN 01



Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.6

THUNDER BAY ICE LOAD TEST SUMMARY

Test #: 1
Run #: 02
Date: Mar-20-84
Scan Begins at: 10:45:30
Duration of Scan: 90 sec
Scan ends at: 10:47:00
Type of test: Alexander Henry
Location of Ship: Ship beyond range of video.

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.45	-0.78	kPa
Hex 1B	0.08	-2.34	kPa
Hex 1C	20.19	-38.62	kPa
Hex 1D	35.85	6.10	kPa
Hex 2A	0.83	-1.12	kPa
Hex 2B	-1.22	-55.25	kPa
Hex 2C	4.02	-14.87	kPa
Hex 2D	55.56	36.98	kPa
Hex 3A	0.48	0.06	kPa
Hex 3B	-1.23	-129.80	kPa
Hex 3C	29.82	17.83	kPa
Hex 3D	78.36	28.67	kPa
Hex 4	3.10	0.37	kPa
Hex 5	15.73	-2.92	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	7.92	1.82	kN/m
Hex 2 aver	4.87	-3.72	kN/m
Hex 3 aver	15.06	-20.76	kN/m
Hex 4 aver	6.20	0.73	kN/m
Hex 5 aver	23.60	-4.38	kN/m

Comments:

FIGURE 5.3

DOCK LOAD DISTRIBUTION

TEST I RUN 02

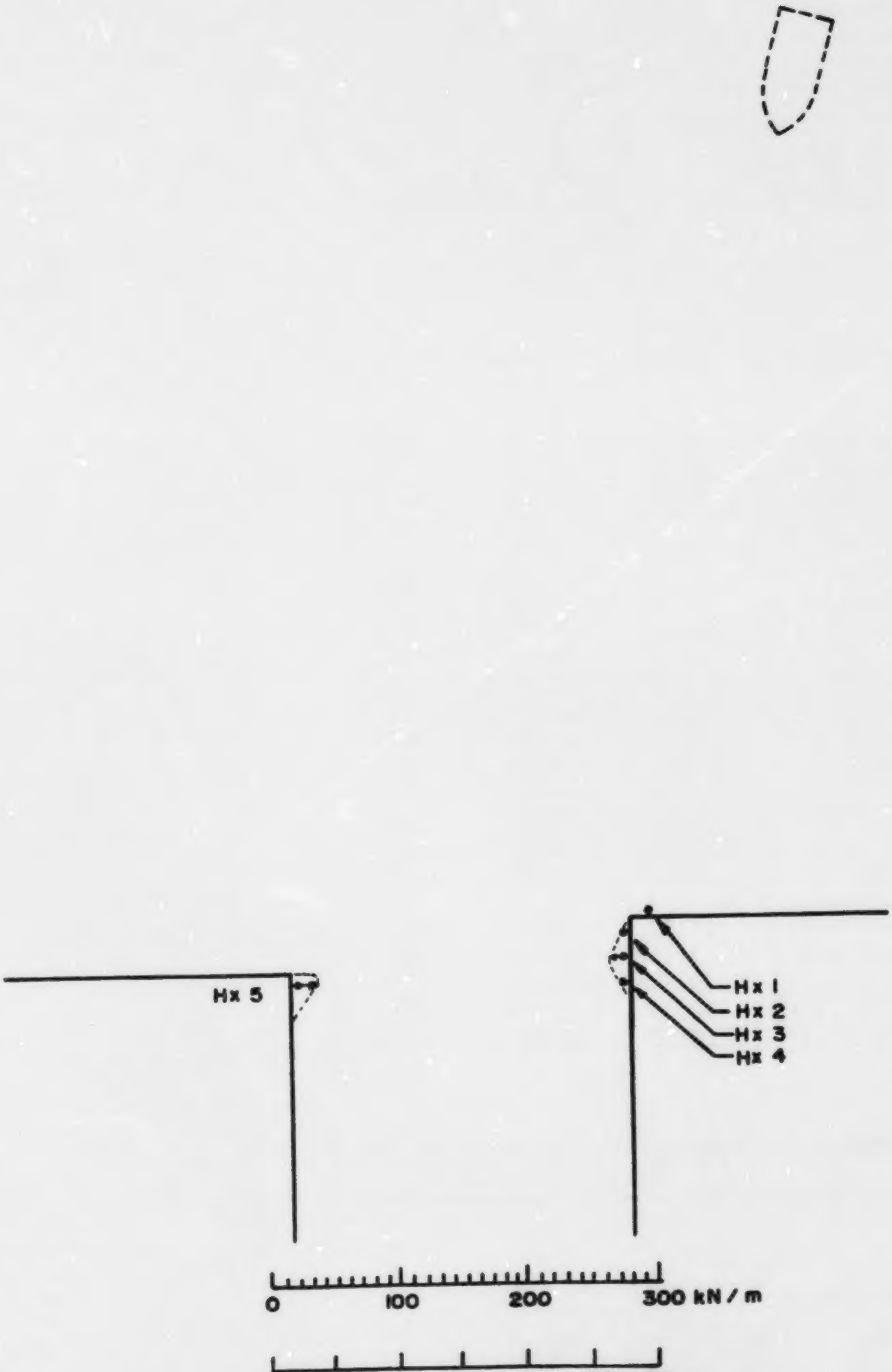

Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.7

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	03
Date:	Mar-20-84
Scan Begins at:	10:47:00
Duration of Scan:	150 sec
Scan ends at:	10:49:30
Type of test:	Alexander Henry
Location of Ship:	120 m E-S-E of dock Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	0.77	-0.49	kPa
Hex 1B	0.34	-2.51	kPa
Hex 1C	47.87	-64.18	kPa
Hex 1D	56.22	-2.09	kPa
Hex 2A	0.62	-1.02	kPa
Hex 2B	40.95	-161.57	kPa
Hex 2C	16.73	-72.80	kPa
Hex 2D	146.04	-17.92	kPa
Hex 3A	1.52	-0.26	kPa
Hex 3B	85.60	-384.57	kPa
Hex 3C	39.21	-13.63	kPa
Hex 3D	267.49	-5.04	kPa
Hex 4	21.07	0.86	kPa
Hex 5	84.44	-23.24	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	14.82	-3.36	kN/m
Hex 2 aver	17.16	-24.79	kN/m
Hex 3 aver	30.54	-54.08	kN/m
Hex 4 aver	42.13	1.73	kN/m
Hex 5 aver	126.66	-34.86	kN/m

Comments: A communication spike at 148 sec.

FIGURE 5.4

DOCK LOAD DISTRIBUTION

TEST I RUN 03

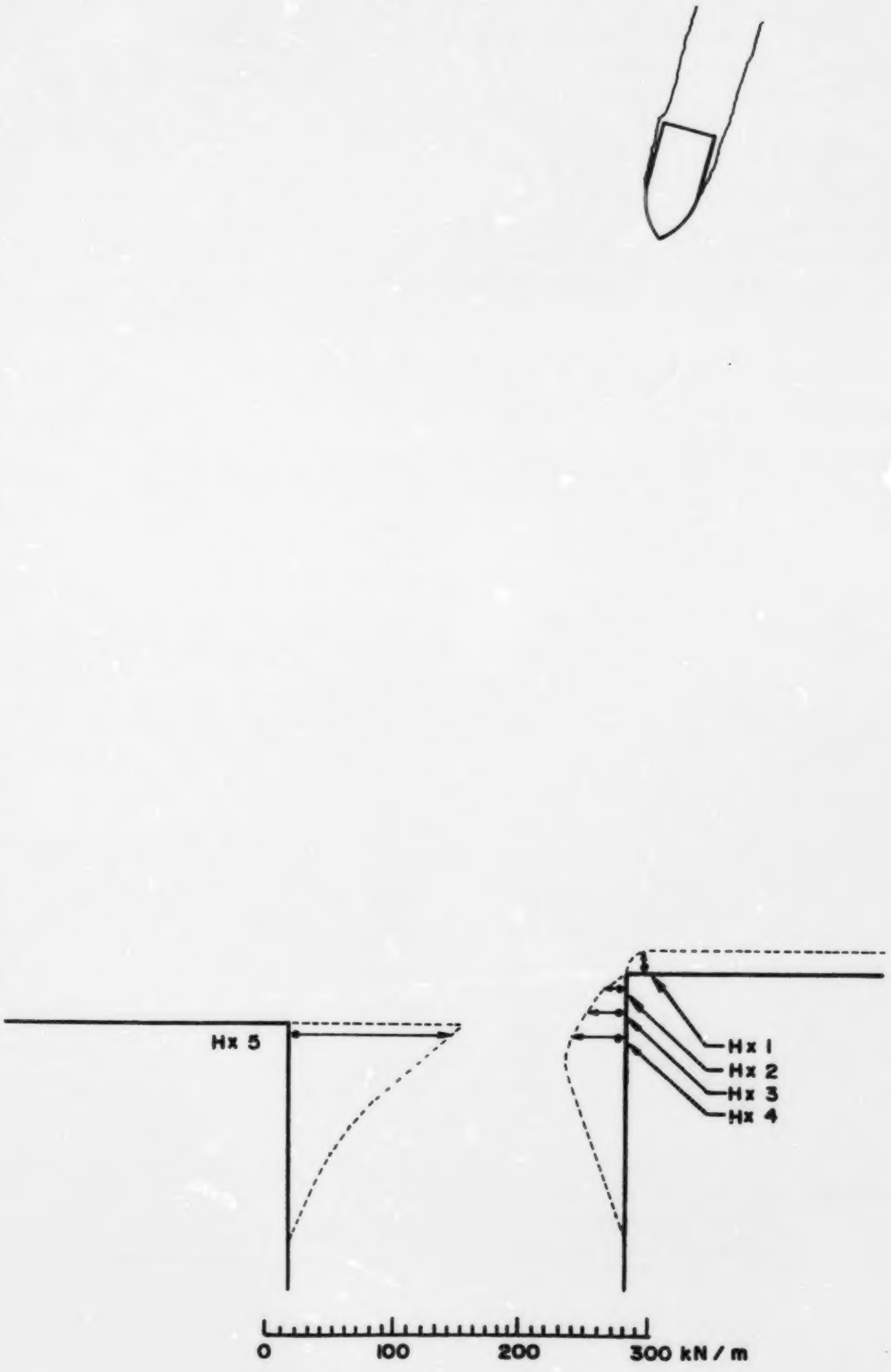

Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.8

THUNDER BAY ICE LOAD TEST SUMMARY

Test #: 1
Run #: 04
Date: Mar-20-84
Scan Begins at: 10:49:54
Duration of Scan: 150 sec
Scan ends at: 10:52:24
Type of test: Alexander Henry
Location of Ship: 80 m E-S-E of dock
Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.45	-2.04	kPa
Hex 1B	0.69	-2.86	kPa
Hex 1C	29.61	-72.44	kPa
Hex 1D	54.06	1.04	kPa
Hex 2A	1.85	-2.97	kPa
Hex 2B	3.27	-144.30	kPa
Hex 2C	6.50	-57.86	kPa
Hex 2D	148.74	15.70	kPa
Hex 3A	5.08	-0.57	kPa
Hex 3B	-6.74	-360.15	kPa
Hex 3C	42.68	0.80	kPa
Hex 3D	251.95	46.18	kPa
Hex 4	22.23	3.35	kPa
Hex 5	45.55	-76.56	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	8.54	-6.57	kN/m
Hex 2 aver	9.05	-17.32	kN/m
Hex 3 aver	23.44	-44.26	kN/m
Hex 4 aver	44.45	6.69	kN/m
Hex 5 aver	68.32	-113.90	kN/m

Comments: Hexpack 5 not functioning for first 56 seconds. A communication spike at 145 seconds.

FIGURE 5.5

DOCK LOAD DISTRIBUTION

TEST I RUN 04

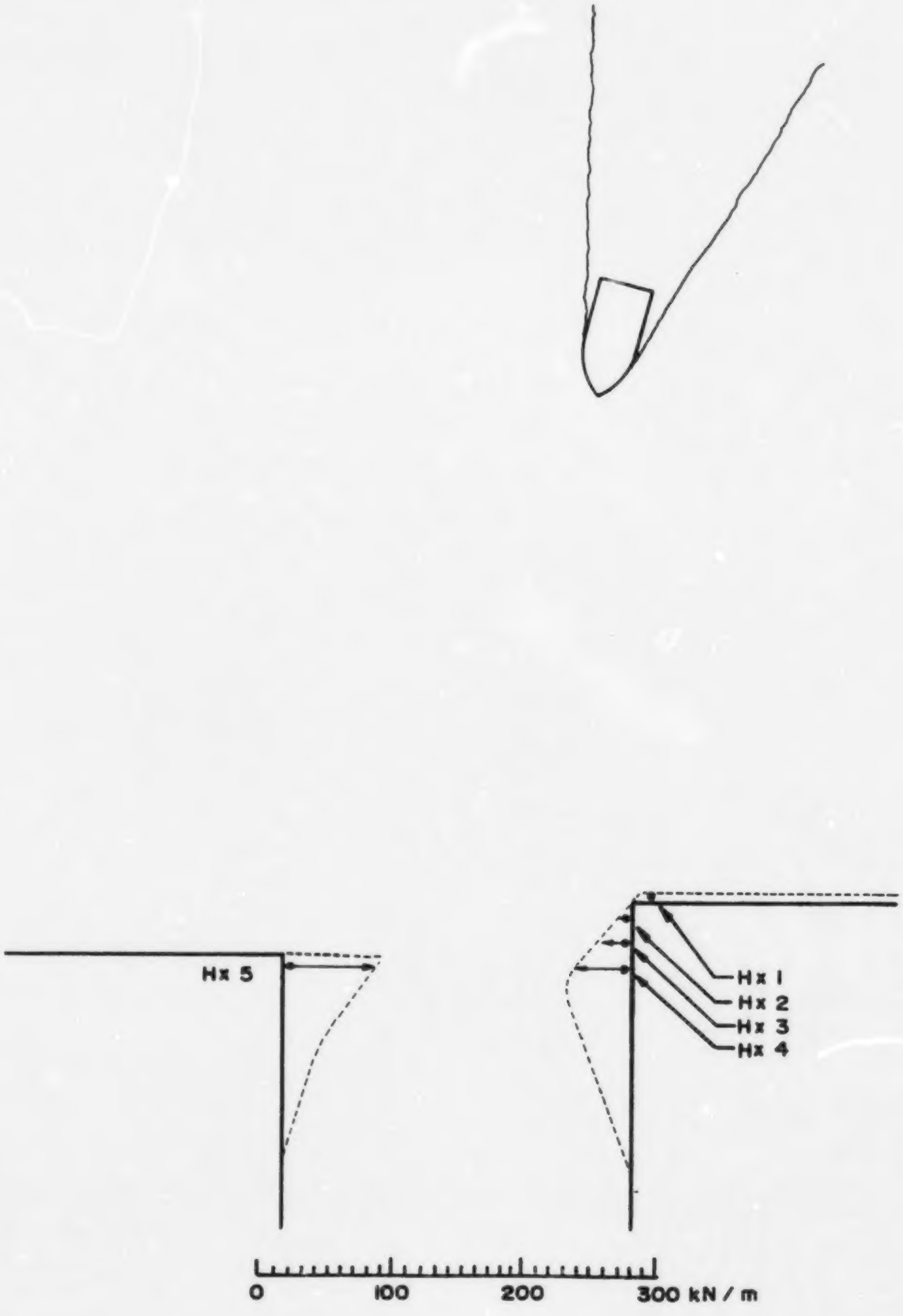

Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.9

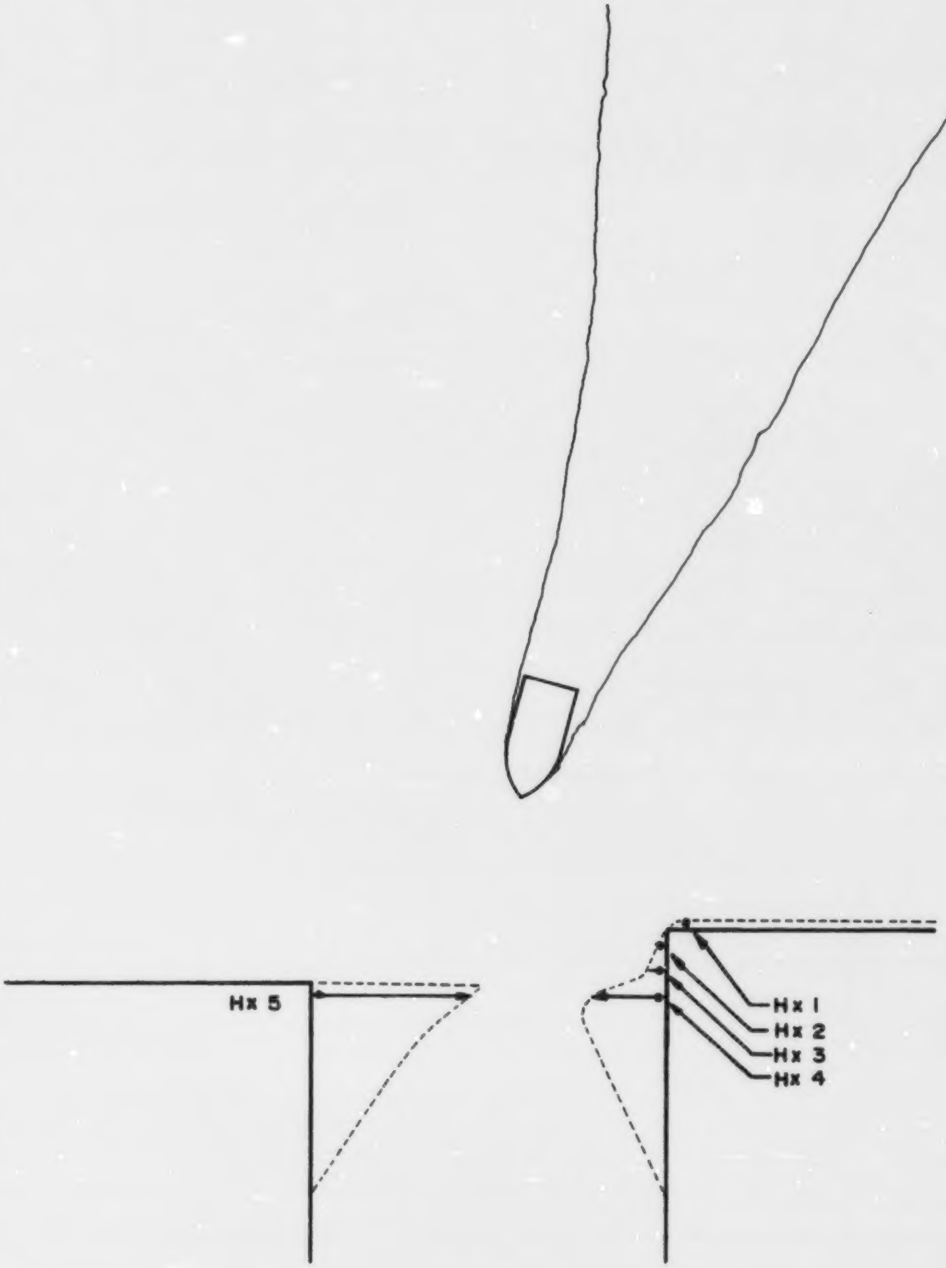
THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	05
Date:	Mar-20-84
Scan Begins at:	10:53:26
Duration of Scan:	140 sec
Scan ends at:	10:55:46
Type of test:	Alexander Henry
Location of Ship:	Starts 60 m E-S-E of dock Ends 15 m east of dock Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.16	-0.10	kPa
Hex 1B	-1.21	-4.41	kPa
Hex 1C	-22.09	-101.75	kPa
Hex 1D	52.23	3.95	kPa
Hex 2A	0.93	-0.71	kPa
Hex 2B	-25.87	-181.40	kPa
Hex 2C	-3.80	-93.33	kPa
Hex 2D	178.06	47.07	kPa
Hex 3A	1.52	-0.05	kPa
Hex 3B	-83.53	-416.46	kPa
Hex 3C	44.07	-29.96	kPa
Hex 3D	355.49	84.27	kPa
Hex 4	28.11	5.58	kPa
Hex 5	79.77	-19.24	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	5.62	-21.79	kN/m
Hex 2 aver	8.22	-24.53	kN/m
Hex 3 aver	11.84	-38.49	kN/m
Hex 4 aver	56.21	11.17	kN/m
Hex 5 aver	119.66	-28.87	kN/m

Comments:

FIGURE 5.6
DOCK LOAD DISTRIBUTION
TEST 1   RUN 05



Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.10

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	06
Date:	Mar-20-84
Scan Begins at:	11:16:22
Duration of Scan:	150 sec
Scan ends at:	11:18:52
Type of test:	Alexander Henry
Location of Ship:	75 m east of dock Breaking north side of channel

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.84	0.38	kPa
Hex 1B	-1.30	-2.68	kPa
Hex 1C	-180.26	-194.39	kPa
Hex 1D	-11.68	-16.63	kPa
Hex 2A	0.93	-1.74	kPa
Hex 2B	4.18	-105.29	kPa
Hex 2C	29.19	-15.57	kPa
Hex 2D	178.62	76.20	kPa
Hex 3A	3.20	1.52	kPa
Hex 3B	-47.30	-312.51	kPa
Hex 3C	56.41	36.77	kPa
Hex 3D	286.32	117.77	kPa
Hex 4	32.58	18.17	kPa
Hex 5	NA	NA	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	-50.13	-54.90	kN/m
Hex 2 aver	37.55	23.64	kN/m
Hex 3 aver	40.67	0.47	kN/m
Hex 4 aver	65.12	36.34	kN/m
Hex 5 aver	NA	NA	kN/m

Comments: Hexpack 5 is not functioning.
Hexpack 1 has broken free.

FIGURE 5.7
DOCK LOAD DISTRIBUTION
TEST I RUN 06

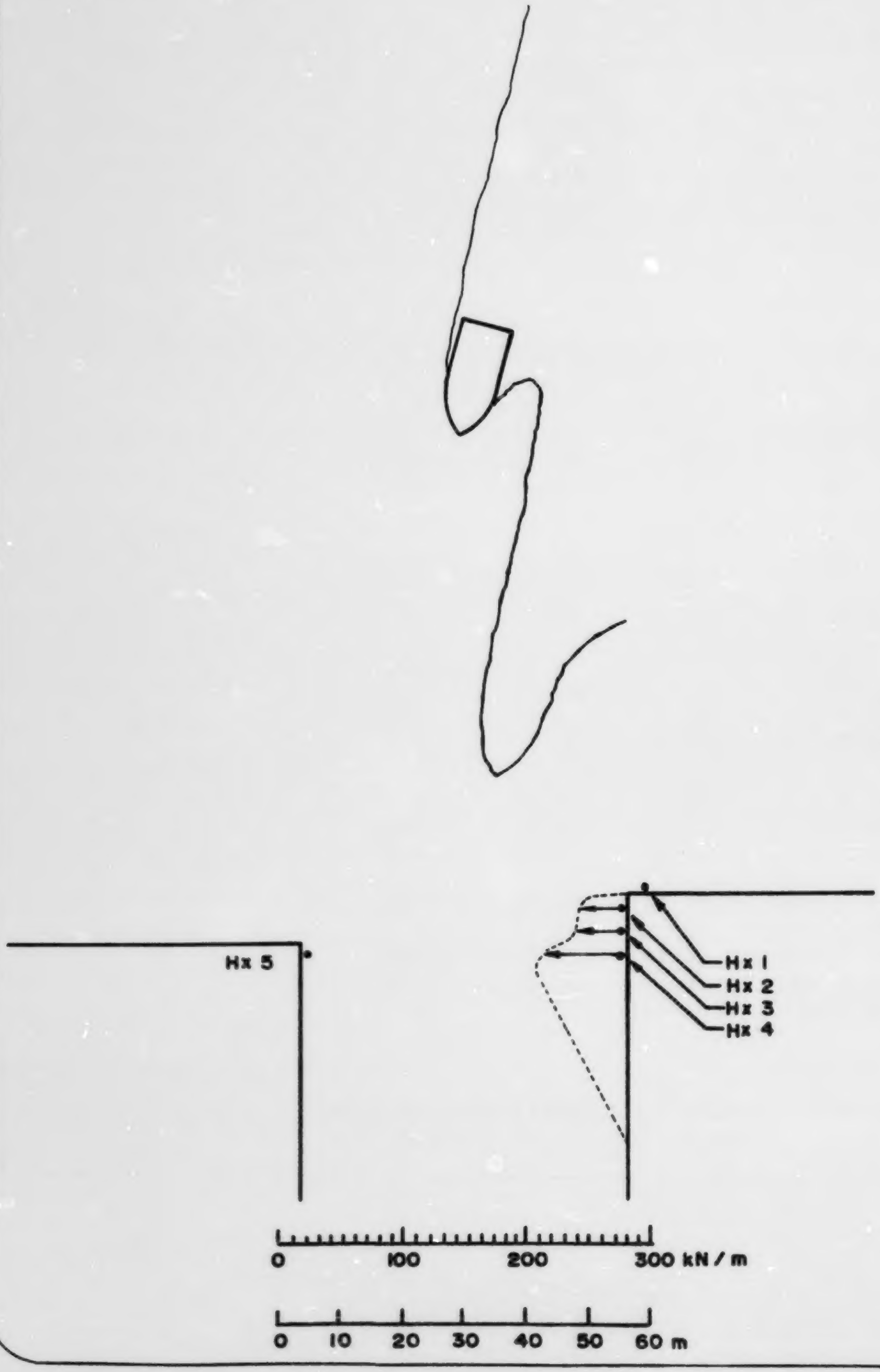

Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.11
THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	07
Date:	Mar-20-84
Scan Begins at:	11:18:56
Duration of Scan:	150 sec
Scan ends at:	11:21:26
Type of test:	Alexander Henry
Location of Ship:	60 m east of dock Breaking north side of channel

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.93	-0.49	kPa
Hex 1B	-1.21	-5.10	kPa
Hex 1C	-181.32	-197.08	kPa
Hex 1D	-12.11	-20.30	kPa
Hex 2A	1.13	-0.61	kPa
Hex 2B	-6.94	-143.89	kPa
Hex 2C	23.08	-46.08	kPa
Hex 2D	202.52	82.55	kPa
Hex 3A	2.99	1.52	kPa
Hex 3B	-75.46	-369.80	kPa
Hex 3C	54.85	4.97	kPa
Hex 3D	362.93	137.25	kPa
Hex 4	36.14	19.00	kPa
Hex 5	87.69	0.00	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	-50.70	-56.99	kN/m
Hex 2 aver	36.54	10.56	kN/m
Hex 3 aver	38.64	-4.56	kN/m
Hex 4 aver	72.27	37.99	kN/m
Hex 5 aver	131.53	0.00	kN/m

Comments: Hexpack 5 not functioning for first 91 sec. Hexpack 1 has broken free.

FIGURE 5.8

DOCK LOAD DISTRIBUTION
TEST I   RUN 07

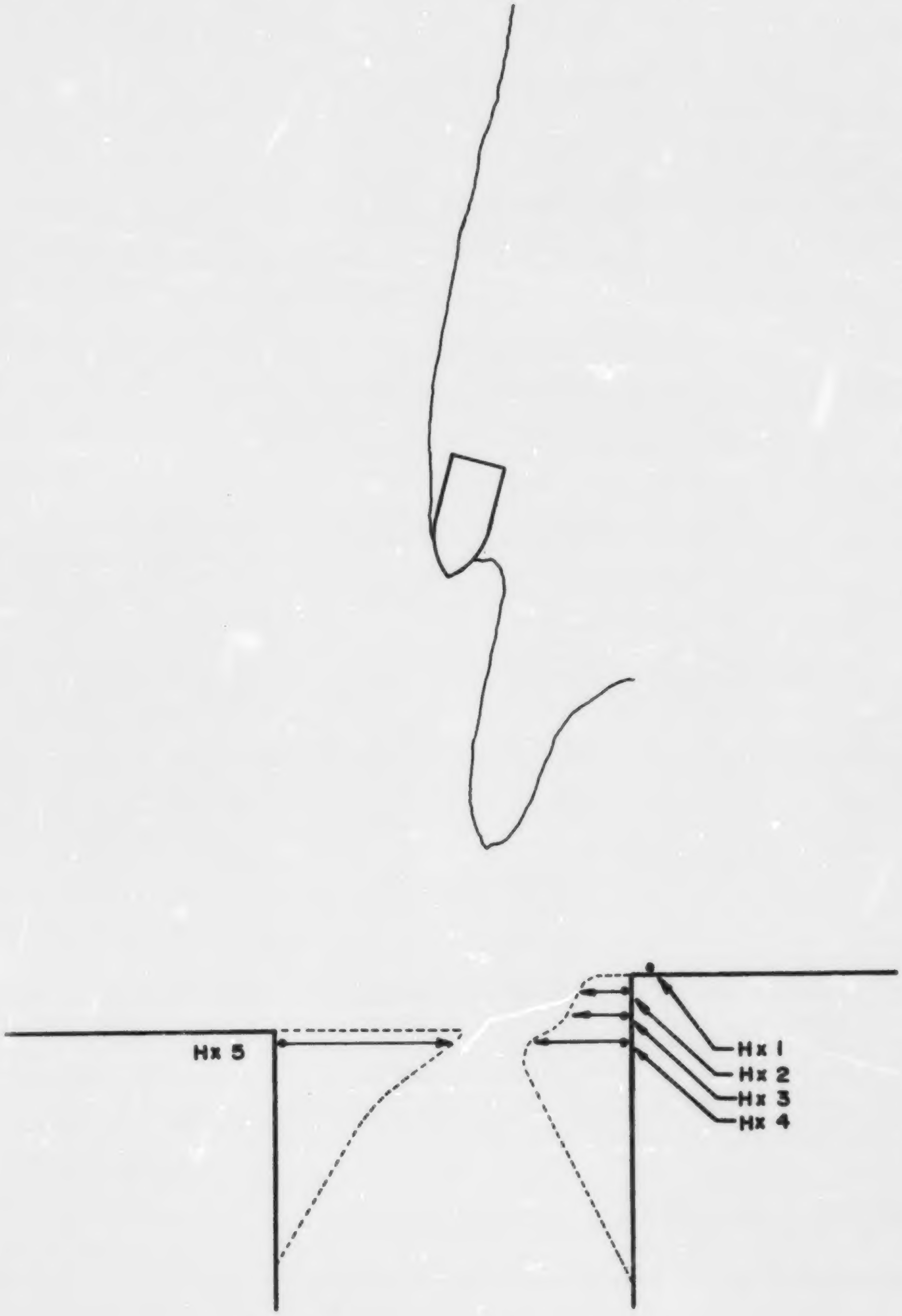

Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.12

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	08
Date:	Mar-20-84
Scan Begins at:	11:23:07
Duration of Scan:	70 sec
Scan ends at:	11:24:17
Type of test:	Alexander Henry
Location of Ship:	45 m east of dock Breaking north side of channel

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.84	-0.49	kPa
Hex 1B	-1.65	-2.68	kPa
Hex 1C	-190.16	-197.66	kPa
Hex 1D	-16.31	-23.75	kPa
Hex 2A	0.83	-0.61	kPa
Hex 2B	-62.63	-218.50	kPa
Hex 2C	-9.99	-137.16	kPa
Hex 2D	229.51	125.31	kPa
Hex 3A	2.78	1.42	kPa
Hex 3B	-223.52	-432.21	kPa
Hex 3C	45.12	-58.12	kPa
Hex 3D	471.95	223.28	kPa
Hex 4	37.38	25.46	kPa
Hex 5	122.33	22.73	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	-53.82	-64.87	kN/m
Hex 2 aver	22.04	-30.50	kN/m
Hex 3 aver	12.35	-14.12	kN/m
Hex 4 aver	74.76	50.91	kN/m
Hex 5 aver	183.49	34.09	kN/m

Comments: A communication spike after 70 sec.

FIGURE 5.9

DOCK LOAD DISTRIBUTION

TEST I RUN 08

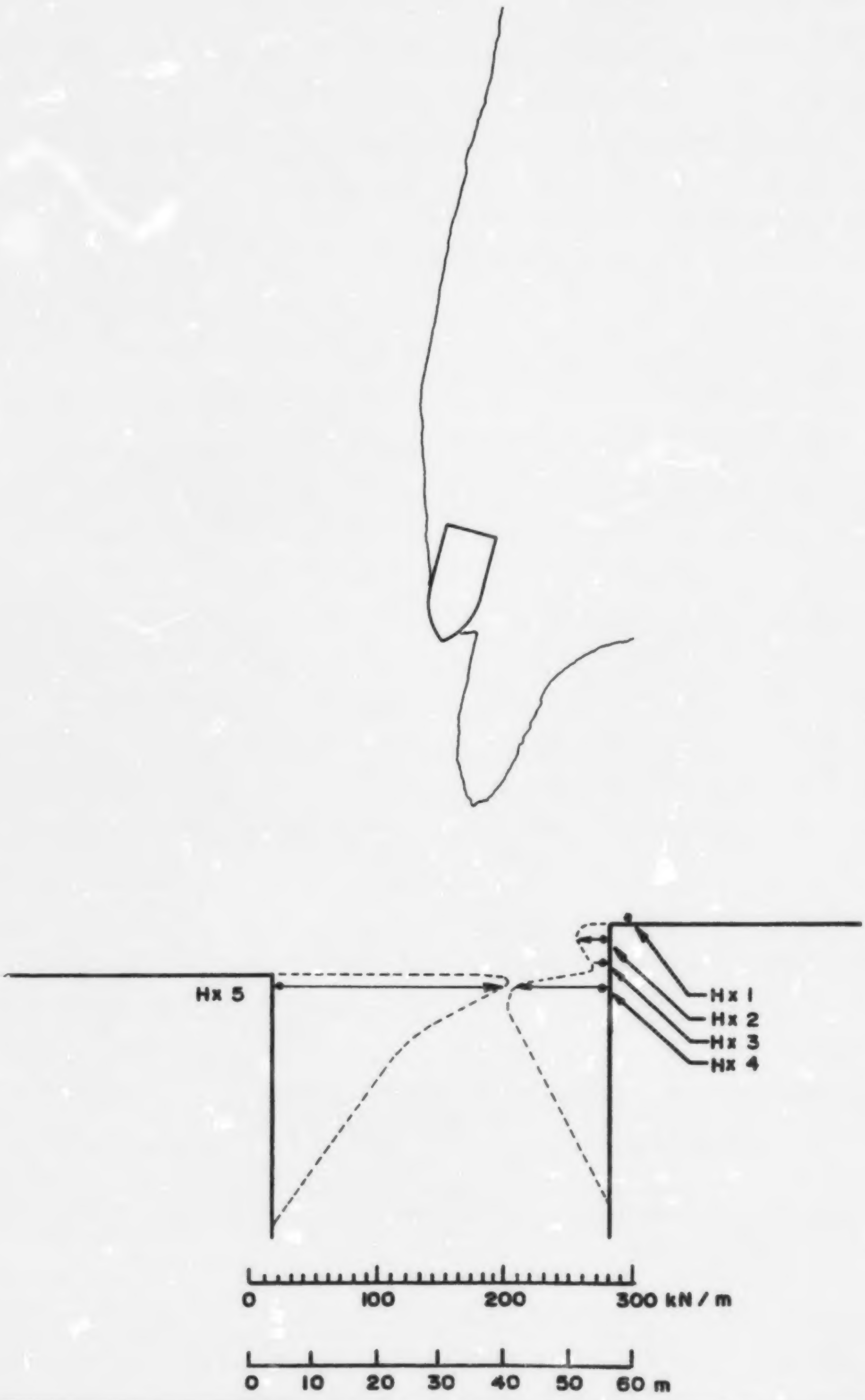

Hx 5
Hx I
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.13

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	2
Run #:	01
Date:	Mar-20-84
Scan Begins at:	15:02:44
Duration of Scan:	150 sec
Scan ends at:	15:05:14
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 15 m east of dock Ends 20 m inside dock Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.29	0.00	kPa
Hex 1B	0.79	0.00	kPa
Hex 1C	2.51	-0.72	kPa
Hex 1D	2.08	-0.65	kPa
Hex 2A	5.19	-15.03	kPa
Hex 2B	140.73	-155.41	kPa
Hex 2C	87.97	-285.78	kPa
Hex 2D	347.97	-299.82	kPa
Hex 3A	7.63	-1.48	kPa
Hex 3B	77.28	-103.07	kPa
Hex 3C	36.10	-296.20	kPa
Hex 3D	370.80	-289.86	kPa
Hex 4	12.74	-99.12	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	5.04	-0.98	kN/m
Hex 2 aver	65.00*	-280.00*	kN/m
Hex 3 aver	125.00*	-119.15	kN/m
Hex 4 aver	25.49	-198.25	kN/m

Comments: Periodic communication throughout. Hexpack 2C, 2D, 3C & 3D saturated the analog record.

* Estimated

FIGURE 5.10

DOCK LOAD DISTRIBUTION
TEST 2   RUN 01

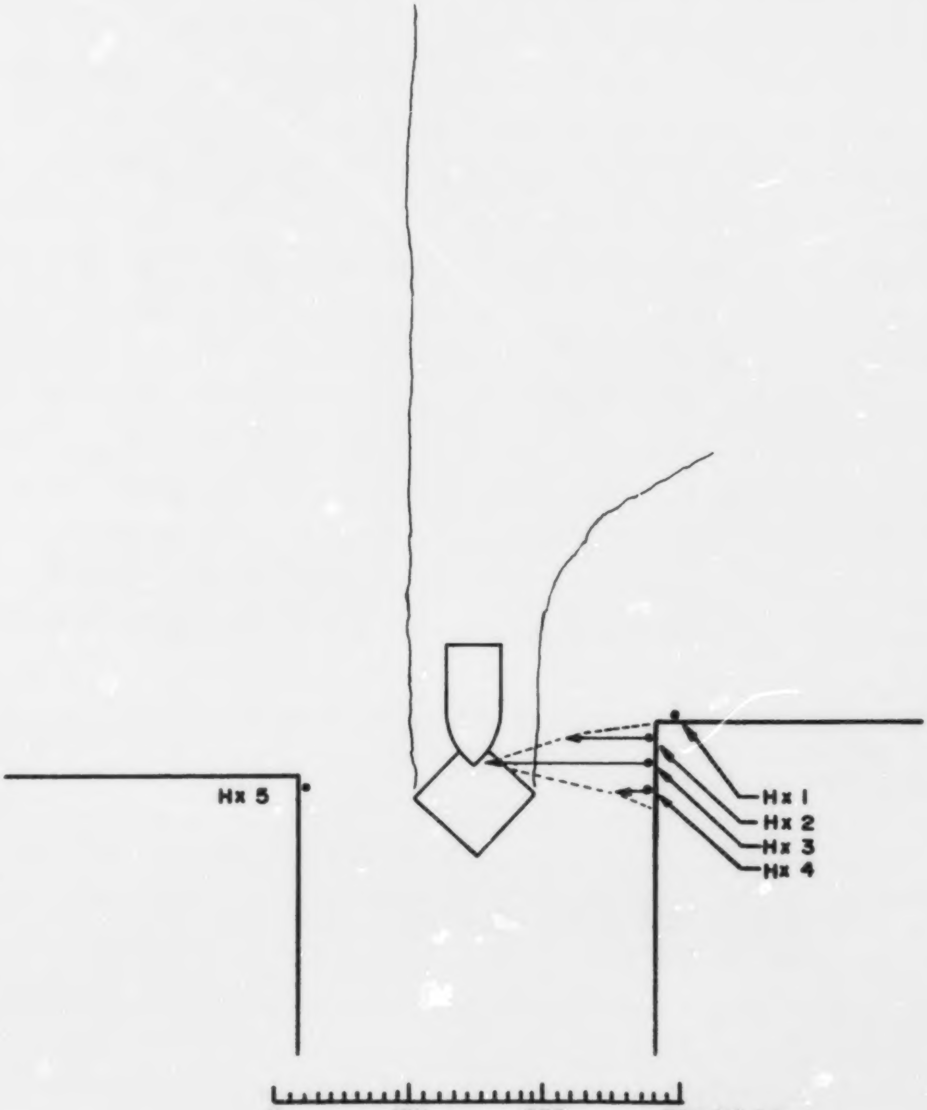

Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

TABLE 5.14

THUNDER BAY ICE LOAD SUMMARY

Test #: 2
Run #: 02
Date: Mar-20-84
Scan Begins at: 15:05:19
Duration of Scan: 130 SEC
Scan ends at: 15:07:29
Type of test: Alexander Henry with ACIB
Location of Ship: Hovering 20 m inside dock

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	0.81	0.23	kPa
Hex 1B	1.07	-1.60	kPa
Hex 1C	4.28	1.11	kPa
Hex 1D	2.71	1.53	kPa
Hex 2A	2.01	-5.59	kPa
Hex 2B	-38.55	-154.58	kPa
Hex 2C	-125.78	-300.00	kPa
Hex 2D	-210.38	-284.51	kPa
Hex 3A	2.50	-1.79	kPa
Hex 3B	-59.95	-107.01	kPa
Hex 3C	-40.55	-350.00	kPa
Hex 3D	359.63	-199.88	kPa
Hex 4	20.78	-91.84	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	3.86	1.14	kN/m
Hex 2 aver	-141.67	-250.00*	kN/m
Hex 3 aver	50.00*	-112.10	kN/m
Hex 4 aver	41.55	-183.67	kN/m

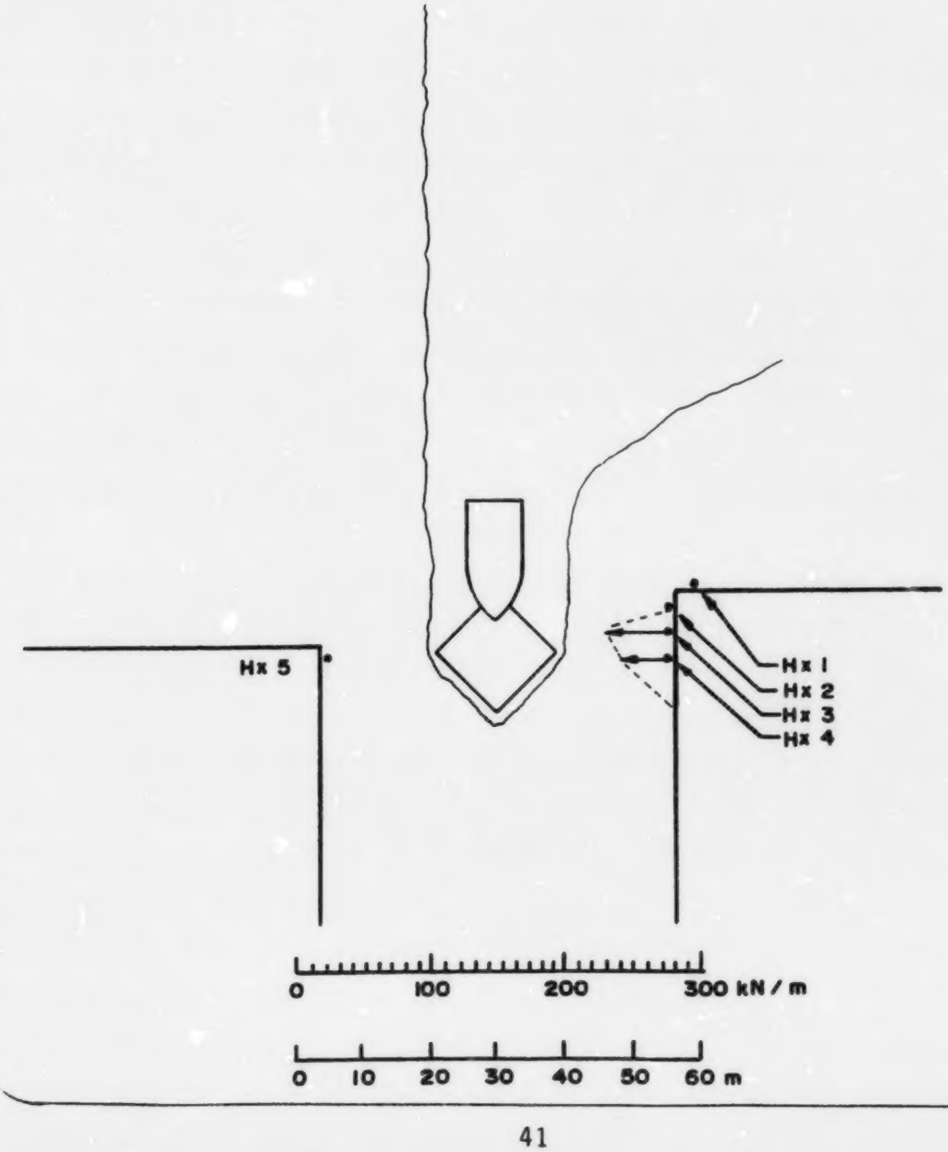
Comments: Periodic communication throughout. Hexpack 2C & 3C saturated the analog record.

* Estimated

FIGURE 5.11

DOCK LOAD DISTRIBUTION

TEST 2 RUN 02


Hx 5
Hx 1
Hx 2
Hx 3
Hx 4
0
100
200
300 kN / m
0
10
20
30
40
50
60 m

Tables 5.13 and 5.14 and Figures 5.10 and 5.11 summarized the ice loads measured while the ALEXANDER HENRY coupled to the ACIB was brought into the slip. During test #2 run #1, the ALEXANDER HENRY started at the edge of the unbroken ice and penetrated approximately 20 metres inside the dock. During this period Hexpacks 2, 3 and 4 measured maximum loads of 65.0, 125.0 and 25.5 kN/m respectively. Contrary to what was observed during test 1, the ice pressure distribution changed so that the peak force was measured with Hexpack 3.

Test 2 run 2 occurred while the ACIB was hovering after completion of the previous ram. During this interval the measured dock loads were lower than during the ram. An interesting observation noted during both tests with the ACIB was that on occasion a periodic oscillation was recorded by the Hexpack. Figure 5.12 shows a sample of this vibration. This frequency of oscillation coincides with the 1 Hz frequency of the ACIB cushion pressure as reported in [3].

Tables 5.15 to 5.18 and Figures 5.13 to 5.16 summarize the ice loads measured during test 3. Run 1 occurs while the ACIB is passing Hexpack 1. Run 2 and 3 occur while the ACIB is approaching and passing Hexpacks 2 and 5. Run 4 occurs while the ACIB is passing Hexpacks 3 and 4. The maximum ice load recorded during test 3 was measured by Hexpack 1 during run #1. The load measured by Hexpack 1 started at zero approximately 15 minutes before run 1 and gradually increased to a climax of 251.92 kN/m as the ACIB passed. Within four minutes of the ACIB passing, the load returned to approximately zero. However, during most of the 15 minutes while the load gradually increased the ALEXANDER HENRY was well clear of the ice. It is not known why this Hexpack recorded such a large change of load over this interval. During similar periods before the previous two tests, all Hexpacks were relatively stable. It is hypothesized that this load may have been caused by thermal stresses in the ice being relieved by the waves caused by the ALEXANDER HENRY. As the thermal stress is relieved it is distributed along the entire dock face. However since the ice surrounding Hexpack 1 had already failed from tests 1 and 2, a stress concentration may have occurred near Hexpack 1. Therefore the ice load measurement of 251.92 kN/m is not expected to have been entirely caused by the entrance of the ALEXANDER HENRY.

The next three successively highest loads measured during test 3 are 178.09, 143.85 and 121.78 kN/m. The first and last values were measured on Hexpack 3 and 4 respectively as the ACIB passed the workhouse. The second value was measured on Hexpack 5 as the ACIB approached the workhouse.

Throughout the entire series of tests, the maximum acceleration recorded was 0.01 g. With the gain of the accelerometer, this signal was of the order of noise. Therefore no meaningful results could be obtained by integrating the signal to produce displacement.

FIGURE 5.12

HEXPACK 2 SHOWING ACIB DYNAMIC RESPONSE

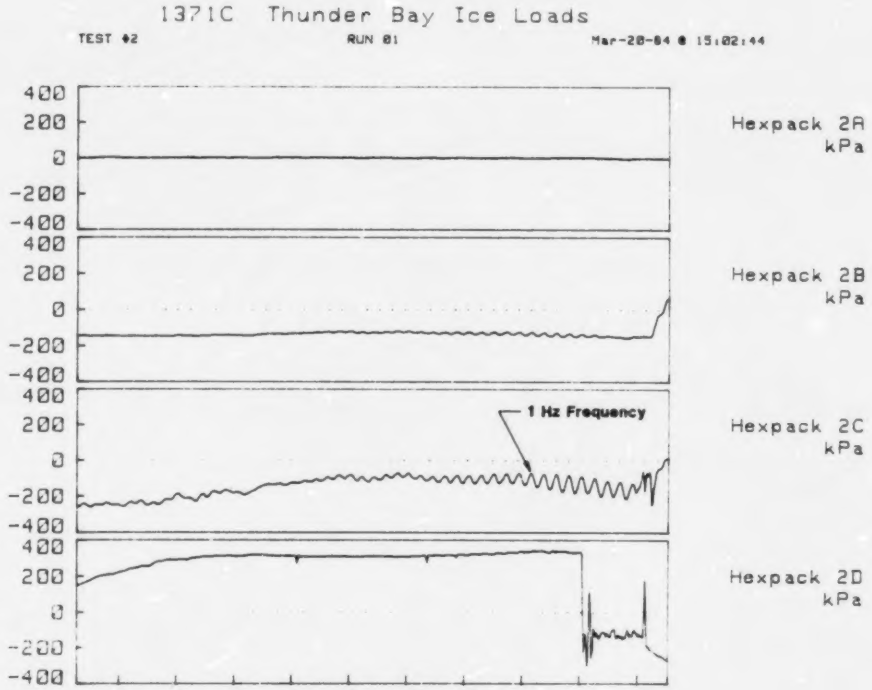


TABLE 5.15

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	3
Run #:	01
Date:	Mar-23-84
Scan Begins at:	10:46:29
Duration of Scan:	150 SEC
Scan ends at:	10:48:59
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 20 m inside dock Ends 45 m inside dock Breaking unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	125.96	-26.57	kPa
Accel 1	0.00	0.00	g'S
Hex 2B	58.04	-0.36	kPa
Hex 2C	22.83	0.42	kPa
Hex 2D	6.37	0.98	kPa
Hex 3B	45.16	38.71	kPa
Hex 3C	-3.87	-11.61	kPa
Hex 3D	66.93	-15.48	kPa
Hex 4	15.90	-11.75	kPa
Accel 2	0.01	-0.01	g'S
Hex 5B	308.92	-0.99	kPa
Hex 5C	21.27	-2.71	kPa
Hex 5D	6.33	-1.55	kPa
Hex 1 aver	251.92	-53.14	kN/m
Hex 2 aver	25.81	0.25	kN/m
Hex 3 aver	52.21	8.60	kN/m
Hex 4 aver	23.85	-17.63	kN/m
Hex 5 aver	121.73	-0.67	kN/m

Comments: Periodic communication throughout.

FIGURE 5.13
DOCK LOAD DISTRIBUTION
TEST 3 RUN 01

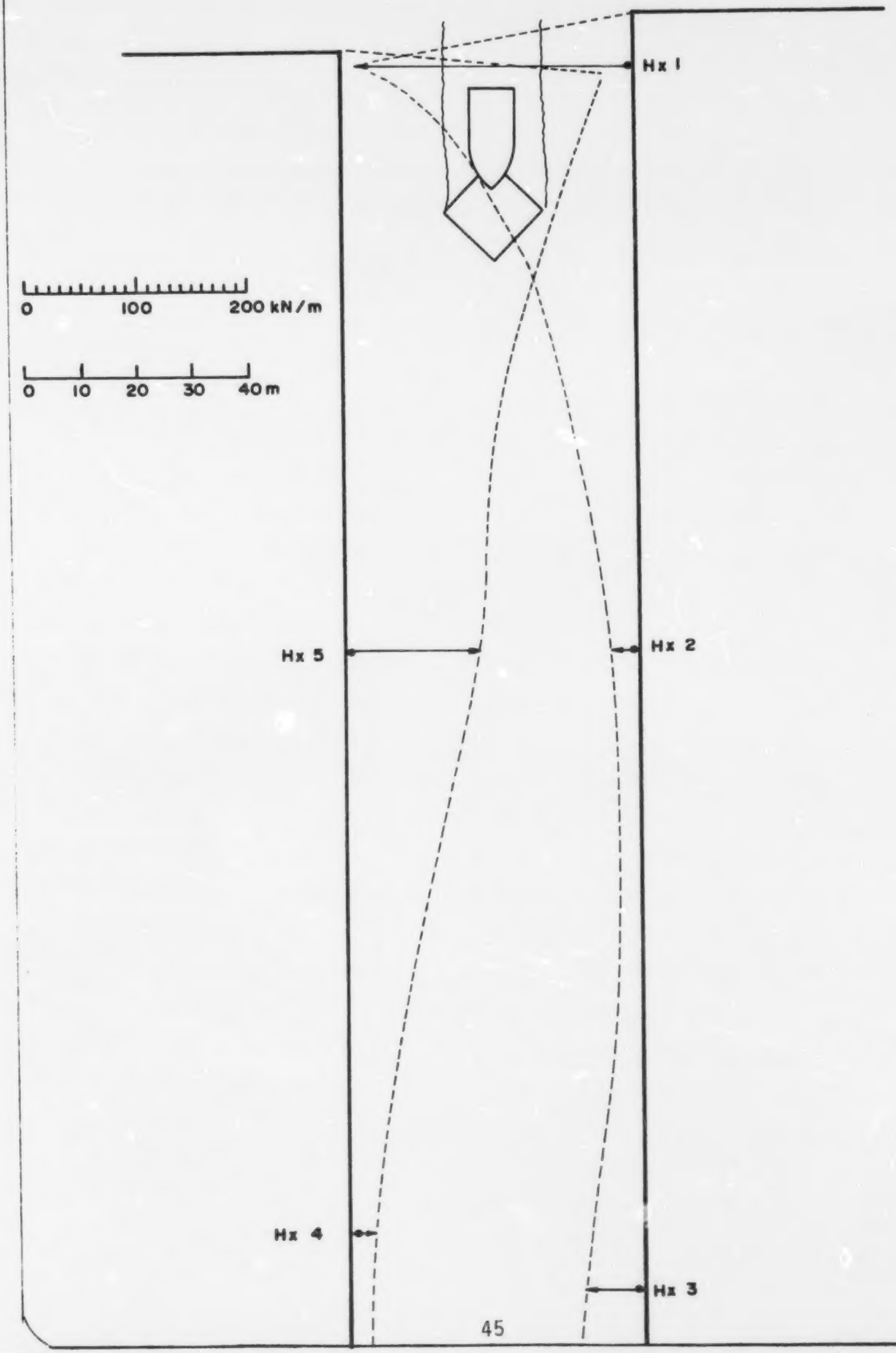

Hx 1
0
100
200 kN/m
0
10
20
30
40 m
Hx 5
Hx 2
Hx 4
Hx 3

TABLE 5.16
THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	3
Run #:	02
Date:	Mar-23-84
Scan Begins at:	10:49:03
Duration of Scan:	150 sec
Scan ends at:	10:51:33
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 45 m inside dock Ends 70 m inside dock Breaking level ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	19.80	-42.55	kPa
Accel 1	0.01	0.00	g'S
Hex 2B	45.70	4.30	kPa
Hex 2C	59.14	15.05	kPa
Hex 2D	4.84	2.15	kPa
Hex 3B	42.58	19.35	kPa
Hex 3C	3.87	-11.61	kPa
Hex 3D	96.77	-23.07	kPa
Hex 4	20.48	-26.07	kPa
Accel 2	0.00	-0.01	g'S
Hex 5B	370.15	44.10	kPa
Hex 5C	20.40	4.94	kPa
Hex 5D	6.77	0.64	kPa
Hex 1 aver	42.58	-80.00	kN/m
Hex 2 aver	24.52	11.21	kN/m
Hex 3 aver	36.13	10.32	kN/m
Hex 4 aver	23.10	-39.11	kN/m
Hex 5 aver	143.85	21.39	kN/m

Comments: Periodic communication throughout.

FIGURE 5.14

DOCK LOAD DISTRIBUTION

TEST 3 RUN 02

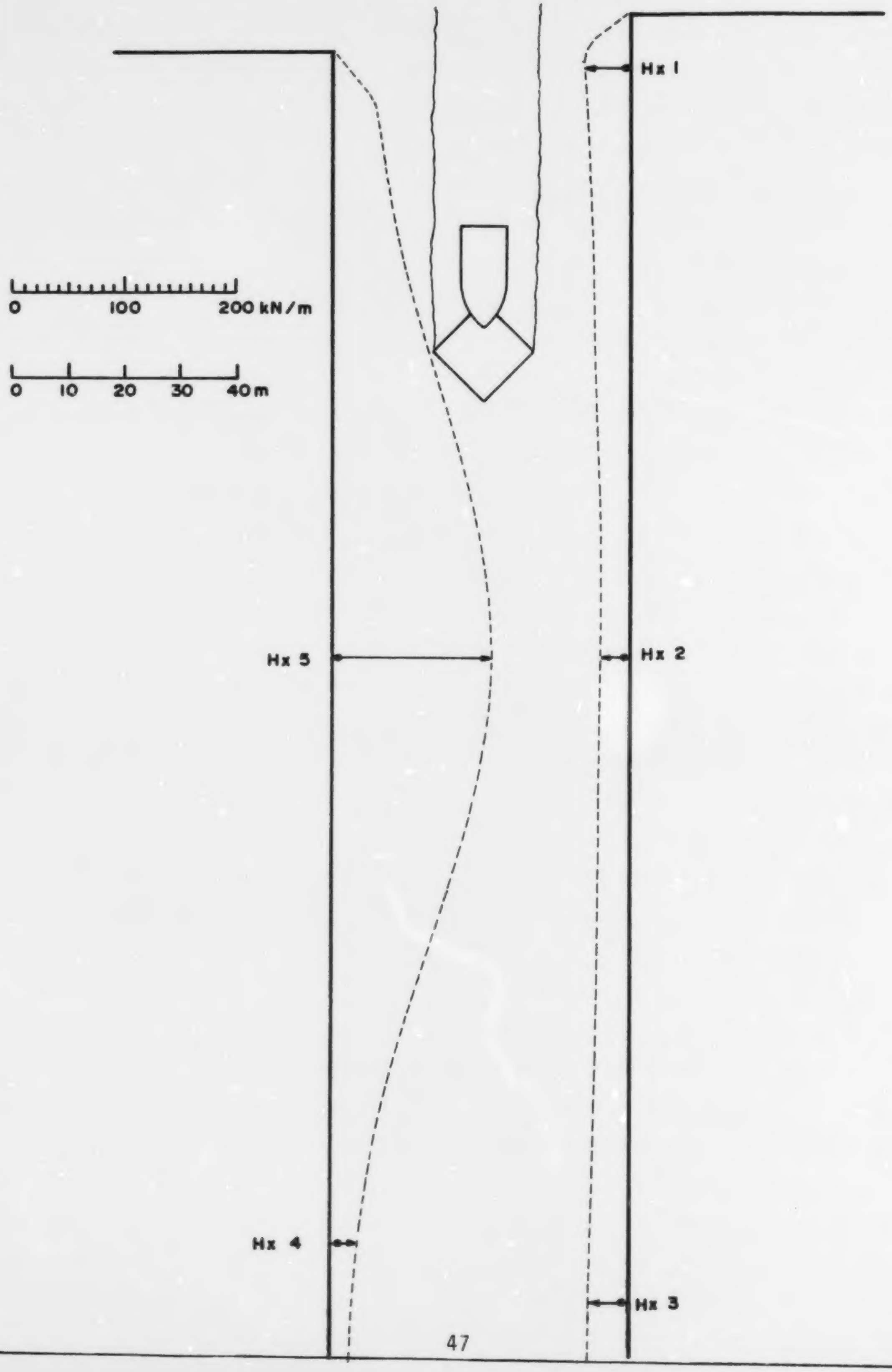

Hx 1
0
100
200 kN/m
0
10
20
30
40 m
Hx 5
Hx 2
Hx 4
Hx 3

TABLE 5.17

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	3
Run #:	03
Date:	Mar-23-84
Scan Begins at:	10:53:20
Duration of Scan:	150 sec
Scan ends at:	10:55:50
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 100 m inside dock Ends 145 m inside dock Breaking unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	-33.12	-46.77	kPa
Accel 1	0.01	0.00	g'S
Hex 2B	5.34	-7.87	kPa
Hex 2C	29.73	-26.68	kPa
Hex 2D	7.77	-2.25	kPa
Hex 3B	42.77	0.00	kPa
Hex 3C	-5.38	-10.75	kPa
Hex 3D	221.36	-6.26	kPa
Hex 4	23.06	-44.06	kPa
Accel 2	0.00	0.00	g'S
Hex 5B	290.80	-1.38	kPa
Hex 5C	28.05	-2.36	kPa
Hex 5D	6.77	-2.86	kPa
Hex 1 aver	-70.97	-93.55	kN/m
Hex 2 aver	8.99	-2.66	kN/m
Hex 3 aver	85.10	11.46	kN/m
Hex 4 aver	30.60	-66.09	kN/m
Hex 5 aver	113.11	-1.55	kN/m

Comments: Periodic communication throughout.

FIGURE 5.15
DOCK LOAD DISTRIBUTION
TEST 3 RUN 03

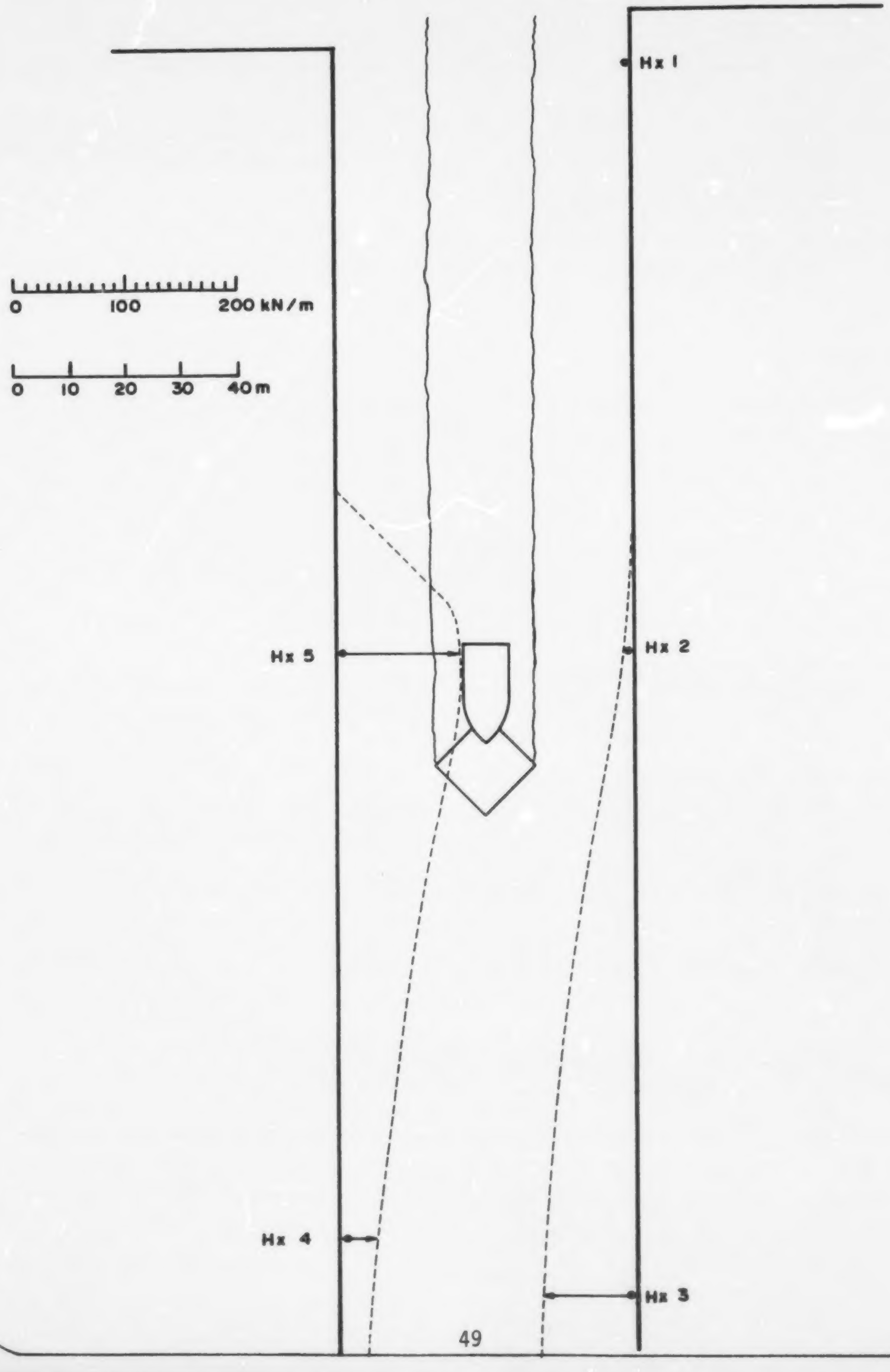

Hx 1
0
100
200 kN/m
0
10
20
30
40 m
Hx 5
Hx 2
Hx 4
Hx 3

TABLE 5.18

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	3
Run #:	04
Date:	Mar-23-84
Scan Begins at:	10:58:16
Duration of Scan:	150 SEC
Scan ends at:	11:00:46
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 205 m inside dock Ends 230 m inside dock

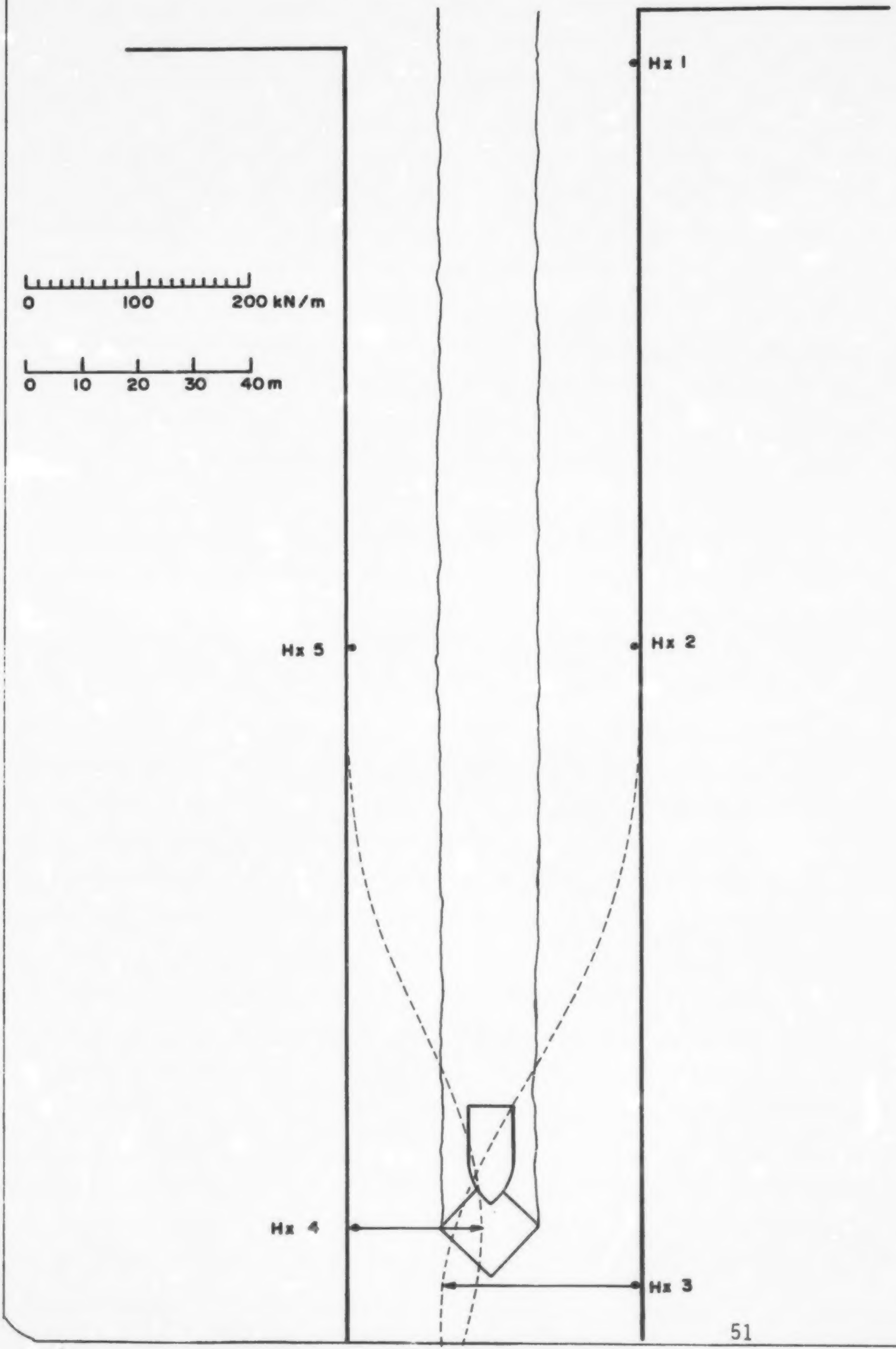
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	-33.53	-44.95	kPa
Accel 1	0.00	0.00	g'S
Hex 2B	-5.59	-9.98	kPa
Hex 2C	3.23	-0.04	kPa
Hex 2D	1.51	-1.29	kPa
Hex 3B	67.25	0.00	kPa
Hex 3C	306.16	-13.07	kPa
Hex 3D	378.96	-21.02	kPa
Hex 4	81.19	-68.21	kPa
Accel 2	0.00	-0.01	g'S
Hex 5B	0.78	-3.15	kPa
Hex 5C	9.28	-0.45	kPa
Hex 5D	4.14	-5.71	kPa
Hex 1 aver	-67.05	-89.90	kN/m
Hex 2 aver	-0.40	-3.51	kN/m
Hex 3 aver	178.09	3.29	kN/m
Hex 4 aver	121.78	-102.32	kN/m
Hex 5 aver	3.95	-2.52	kN/m

Comments: Periodic communication throughout.
Hexpack 3C saturated the analog record.

FIGURE 5.16

DOCK LOAD DISTRIBUTION

TEST 3 RUN 04


0
100
200 kN/m
0
10
20
30
40 m
Hx 1
Hx 2
Hx 3
Hx 4
Hx 5

5.3 Thermal Loads

During a 36-hour period between March 18 and March 20, the ice pressures due to thermal stresses were measured. During this same time both air temperature and ice temperatures were recorded. Figure 5.17 shows how the ice temperature profile changed with time. The temperature at the top of the ice ranged between -3.9°C and -.1°C, while the temperatures near the bottom ranged between -1.7°C and -0.2°C. This temperature fluctuation as well as temperature differential produce thermal stresses which were recorded by the Hexpacks. As reported by Bomeng [2], the thermal ice pressure is greatest in the top 30 cm of the ice and gradually diminishes with depth. This agrees with the measurements recorded by the Hexpacks. Figure 5.18 shows the time series plots of Hexpack 2 averaging the measurements hourly. Segment A is virtually out of the ice and as such records little pressure. However segments B, C and D record progressively lower pressures. The maximum pressure fluctuation due to thermal effects is recorded by segment B, varying between +50 kPa to -275 kPa. Figure 5.19 shows the air temperature variation during this same period and Figure 5.20 shows both the maximum and minimum dock load as measured by Hexpack 5. The dock load ranged between +100 kN/m and -300 kN/m.

FIGURE 5.17

ICE TEMPERATURE PROFILES at MANITOBA POOL #1

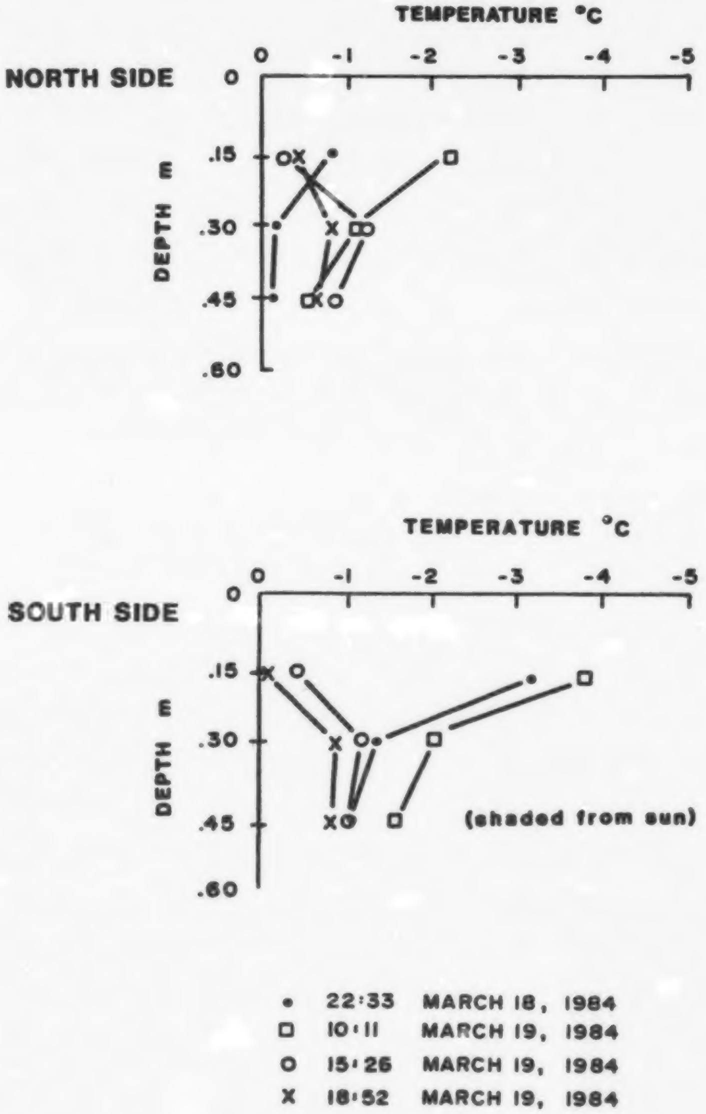


FIGURE 5.18

ICE PRESSURE VARIATION DUE TO THERMAL CHANGE

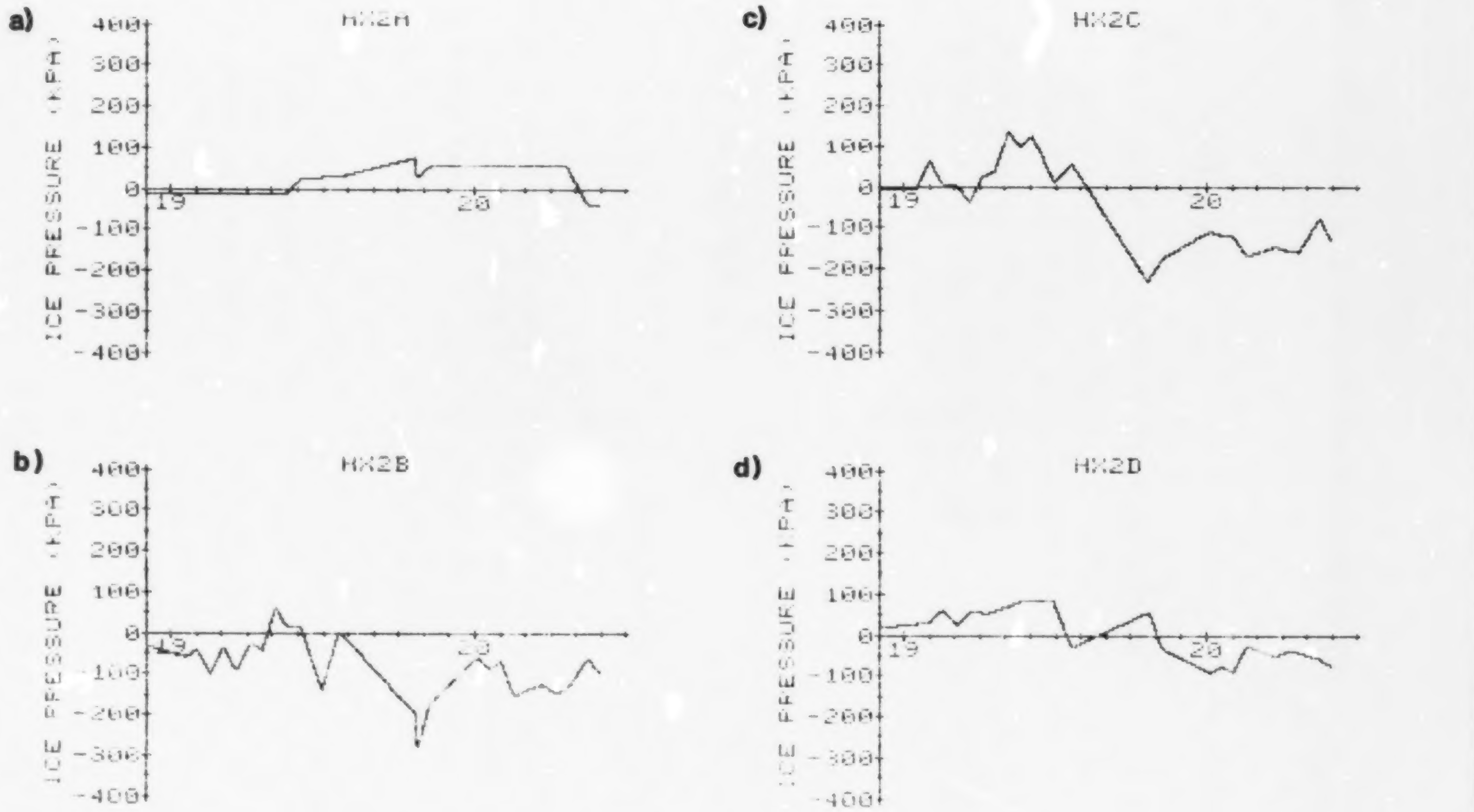


FIGURE 5.19

AIR TEMPERATURE OSCILLATION

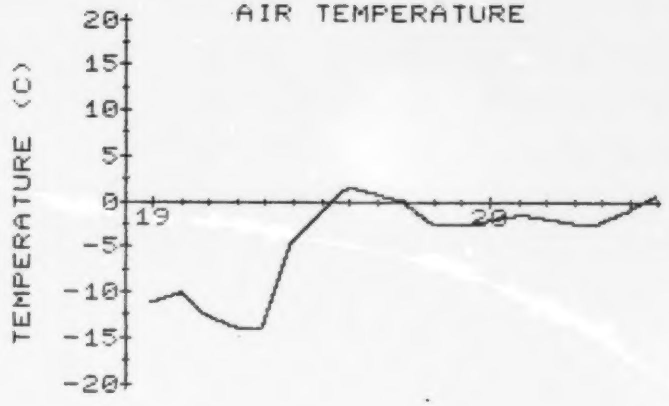
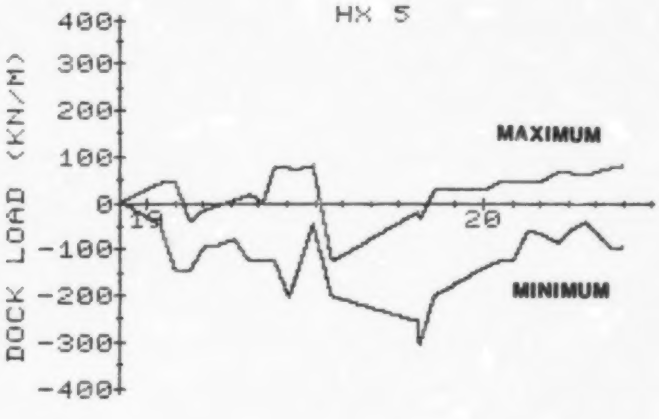


FIGURE 5.20

THERMAL ICE LOADS



6. CONCLUSIONS

1. The maximum allowable force along the full length of the dock was 365 kN/m, as calculated by V.B. Cook Company Ltd. of Thunder Bay.

2. The maximum force measured due to thermal expansion of the ice was between 300 kN/m and -100 kN/m.

3. The peak force measured when the ALEXANDER HENRY icebreaker approached the entrance of the slip, reached a maximum force of 184 kN/m (Test #1). The force was considered too high and no further tests were carried out with the ALEXANDER HENRY alone.

4. The peak force measured when the ALEXANDER HENRY coupled with the Air Cushion Icebreaking Bow (Test #2) penetrated about 25 m into the slip, recorded a maximum load of 125 kN/m. The ice was not broken by the ACIB, but by the icebreaker bow. The test was stopped.

5. The peak force measured during the penetration of the ALEXANDER HENRY coupled with the Air Cushion Icebreaking Bow (Test #3) to the end of the slip was 178 kN/m.

6. The forces applied on the dock wall as a result of the penetration of a vessel were found to be significant. The forces attainable may exceed the design maximum load if a preloading caused by thermal stresses exists. These latter are at maximum when the temperature of the ice increases significantly in a short period of time.

7. The pressure applied on structures located around navigation channels may be successfully evaluated using experimental and analytical techniques.

7. RECOMMENDATIONS

1. The use of a conventional icebreaker to break up an intact ice cover inside the slips at Thunder Bay must not be permitted.

2. The Air Cushion Icebreaking Bow has proven to be an efficient and safe bow to use in the slips. Other vessels with advanced bows that break ice with a downward force may also be used safely.

3. The pressure applied on structures located around navigation channels should be evaluated using experimental and analytical solutions. Field experiments can be carried out by deploying a number of pressure transducers in ice and measuring the forces associated with the passage of a vessel nearby.

4. Field experiments are expensive and should be complemented by laboratory experiments to evaluate the effect of the following variables:

   ° Ice thickness
   ° Ice properties
   ° Vessel distance from the structure
   ° Structure stiffness
   ° Structure shape
   ° Vessel entering velocity
   ° Bow shape
   ° Thermal stress

5. The results of these laboratory experiments should be compared to the limited results obtained from the field experiments including the present study and compared as well to the finite element model results. Such a study should provide a complete understanding of the associated forces applied on structures surrounding the navigation channel due to ship traffic.

8. REFERENCES

[1] Abdelnour, R. et al, "Ice Management in Thunder Bay Harbour, Winter 1984; Volume I; Cannon Bubbler Experiments", TP5834E. Prepared for Transportation Development Centre, by Arctec Canada Limited, July 1984.

[2] Bomeng, X., "Pressure Due to Expansion of Ice Sheet in Reservoirs", IAHR Symposium on Ice, 1981.

[3] Dubois, J. et al, "Testing and Evaluation of the ACIB in Thunder Bay Harbour",TP4083E. Prepared for Transportation Development Centre, by Arctec Canada Limited, March 1983.

[4] Eranti, E. et al, "Ice Control in Finnish Harbours", 7th International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC '83), Helsinki, 1983.

[5] Gill, R.J. and A.B. Cammaert, "Ice Control for Arctic Ports and Harbours",TP3967. Prepared for Transportation Development Centre, Transport Canada, January 1983.

[6] Abdelnour, R. and M. Sayed, "Technological Alternatives to the Use of the CCGS Icebreakers at Thunder Bay Harbour", report prepared for Marine Research and Development - Energy, Transport Canada by Arctec Canada Limited, July 1982.

APPENDIX A

V.B. COOK REPORT

INSTRUCTION

V. B. Cook Co. Limited was retained by Arctec Canada Limited to compute the maximum lateral loads that can safely be sustained by the structures bordering a grain elevator slip. Ice breaking procedures in the slip are expected to impose lateral forces on the surrounding building systems.

The terms of reference, as presented by Mr. R. Abdelnour, are summarized below: (Appendix 'A' is a copy of the reference documents.)

1. The slip to be investigated is located in Thunder Bay. It is bounded by the properties of United Grain Growers 'M' (UGGM) and Manitoba Pool #1 (Man. Pool 1). (See Drawing No. 1 and 2, Appendix 'B'.)

2. Establish the maximum safe lateral loads an ice sheet may impart to the slip perimeter structures without causing damage. Both directions, perpendicular and parallel to the dock face, are to be considered.

3. Displacement calculations are not required.

SUMMARY

The analysis of the UGGM and Man. Pool 1 structures has been completed. The revetment sheet piling is the critical structural element. The governing factor used to establish the maximum allowable lateral loads is the capacity of the dock system to support the upper end of the sheet piling.

The maximum safe load, both perpendicular and parallel to the dock face, is 365 KN/m. Analysis indicates that the structures on both sides of the slip are similar in resistive capacities.

The UGGM outshore dock is the most flexible structure in the slip system. The outshore annex dock of Man. Pool 1 is less flexible and the UGGM workhouse dock is the least flexible.

DESCRIPTION

The slip that was studied is located in the Thunder Bay harbour. (See Drawings No. 1 and 2, Appendix 'B'.)The nominal water depth is 8.3 m.

The Man. Pool 1 annex No. 3 dock structure extends to the outshore end of the slip. The annex building and dock are supported on piles. The dock is integrated with the annex through the foundation mat. The top of the revetment sheet piling is anchored in the concrete dock and tied back to battered piles. The bottom of the sheet piling is embedded in clay and dense till. (See Drawing No. 3, Appendix 'B'.)

The outshore end of the UGGM facility is comprised of a revetment and concrete dock. The top of the sheet piling is cast into the dock and tied back to anchor walls. The bottom of the piling is embedded in the subsoils. The dock is backed by compacted granular fill. (See Drawing No. 4, Appendix 'B'.)

The revetment system at the UGGM workhouse is similar to that of the Man. Pool 1 annex.

An ice breaker will be used to attempt to open the slip. During the breaking activities, it is expected that lateral loads will be imposed on the slip revetments through the existing ice sheet.

PROCEDURE

Structural analysis was carried out for three locations in the slip. These include the outshore end of Man. Pool 1 storage annex No. 3, the UGGM outshore dock and the UGGM workhouse. Calculations are based on a unit-length-of-dock.

It was established that a superstructure, such as an annex, would not be subjected to damaging forces prior to evidence of overstressing in the dock structure. This postulate has been supported by the incident of a ship colliding with the Canada Malting dock. The ship caused extensive damage to the dock without affecting the buildings.

The sheet piling is the structural element subjected to lateral loads transmitted by the ice. It resists loads through 'beam' action. The dock structure supplies one reaction for the 'beam' and the subsoils behind the piling supply the second.

The dock structure derives its lateral capacity from a combination of piling (battered and vertical) under the dock and grain elevator superstructures, passive earth pressure on the superstructures, and the relaxation of the pretensioned sheet pile tie-rods. The subsoils supply support for the sheet piling through passive earth pressure action.

The limiting factor in the analyses is the maximum reactive capacity of the dock structure. Values for this unknown were established.

The piling was modelled using three approximations.

1. simple beam, partially loaded with a uniform ice load.

2. simple beam, fully loaded with a uniform ice load.

3. simple beam with cantilever overhang, fully loaded with a uniform ice load.

Since the interest lies in maximum lateral loads, the analyses required two structural criteria to be satisfied simultaneously. The maximum reaction at the dock level must be attained. The sheet piling must reach maximum allowable bending stresses.

Maximum lateral pressure on the sheet piling was determined while optimizing the revetment capacity. Corresponding ice thicknesses were calculated. Subsoil passive earth pressure values were checked to ensure that the second 'beam' reaction could be realized. Maximum acceptable forces perpendicular to the face of the dock resulted from this evaluation.

The procedure for establishing the maximum allowable force parallel to the dock is similar. Considering dock anchorage, subsoil shear and pile interation, the maximum acceptable value was determined.

Local failure of the sheet piling and the 'opening' of the piling interlock were also investigated. Information about interlock tensile capacity is limited. Field measurements were required to verify the assumed values. (See Drawing No. 5, Appendix 'B').

As the thickness of the ice increases, the lateral load imparted to the sheet piling is distributed over an increasing length of piling. The resisting capacity of the revetmet is enhanced by this load distribution mechanism. The effect of ice thickness was studied to determine if it was significant.

CONCLUSIONS

The superstructures will not be directly affected by lateral loads on the revetments caused by the ice breaking procedures.

The effect of lateral loading on various beam approximations of the sheet piling was studied. Excessive ice thickness (5.3m) is required to simultaneously establish the maximum reaction at the dock level and the maximum allowable bending in the sheet piling. Therefore, a single governing factor, the maximum reaction that the dock can safely supply to the revetment, was used to establish the safe lateral loads which may be imposed. Bending stresses in the sheet piling are always within acceptable limits.

Calculations were done to consider the effects of ice thickness on the total capacity of the revetment system. A theoretical ice thickness of zero is the lower limit. This corresponds to a lateral load equal to the maximum dock reaction. As ice thickness increases, the system capacity increases dramatically, becoming assymtotic with larger ice depths. (See Table 1.)

TABLE 1

Ice Thickness (m)	Revetment Capacity (kN/m) Perpendicular to Dock Face
0.0	240
0.3	345
0.9	460
1.89	480

The maximum acceptable lateral loads for the locations studied are listed in Table 2. The values, based on a .3m (12 inch) ice thickness, are the total maximum allowable load, including preload, that can be imparted to the sheet piling while maintaining a stable structural system.

TABLE 2

	Revetment Capacity (kN/m)	
Location	Perpendicular To Dock Face	Parallel To Dock Face
Man. Pool 1 Annex No. 3	350	400
UGGM Outshore Dock	345	---
UGGM Workhouse	560	---

The probability of the existence of the appropriate conditions for local sheet piling failure is remote. The results of this investigation are not a consideration.

RECOMMENDATIONS

It is believed that ice thickness will exceed .3m at the time ice breaking is attempted. It is therefore recommended that the lateral force perpendicular and parallel to the dock not exceed 365 kN/m. This value represents a total load.

These maximums apply to both revetments which line the slip that was investigated for this report.

APPENDIX B

ICE FORCE CALCULATIONS

ICE FORCE ON THE DOCK

The forces that will be applied on the dock during the penetration of the ALEXANDER HENRY have been calculated using a finite element model. The finite element program used is Stardyne available on multiple access on-line computer packages.

The program was run by assuming the following:

1. The ALEXANDER HENRY icebreaker will be used without assistance by the ACIB.
2. The ice thickness is 1.0 m.
3. The icebreaker will be breaking ice in continuous mode.
4. The dock walls are completely rigid (use of very large spring constant).

The plan of the slip was divided into elements as shown in Figure 1. The force applied from the ship was the input to the model (A). The output was calculated by the model (B). The results of the computer model exercised with the above conditions showed a maximum value of 87.8 kN/m (see Figure 2). A run was also made with the dock having a spring constant of 0.7 mm/kN, and the force measured was 3.0 kN/m (see Figure 3).

The force allowed on the dock calculated based on the construction properties of the structure was 366 kN/m (25 kips/ft) according to calculation provided by V.B. Cook Company (see Figure 4).

The calculations above considered that the ice is 1.0 m thick, however, this is a conservative estimate since the ice thickness in the slip by the time of testing is not more than 0.75 m. Also, in the calculation it was considered that the icebreaker ALEXANDER HENRY will break the ice continuously, but it is well known that the HENRY cannot break more than 0.4 m of ice. The final point considered that may have increased the force significantly is the assumption of the dock spring constant as infinitely rigid.

FIGURE 1

MESH USED FOR THE FINITE ELEMENT PROGRAM TO REPRESENT THUNDER BAY HARBOUR

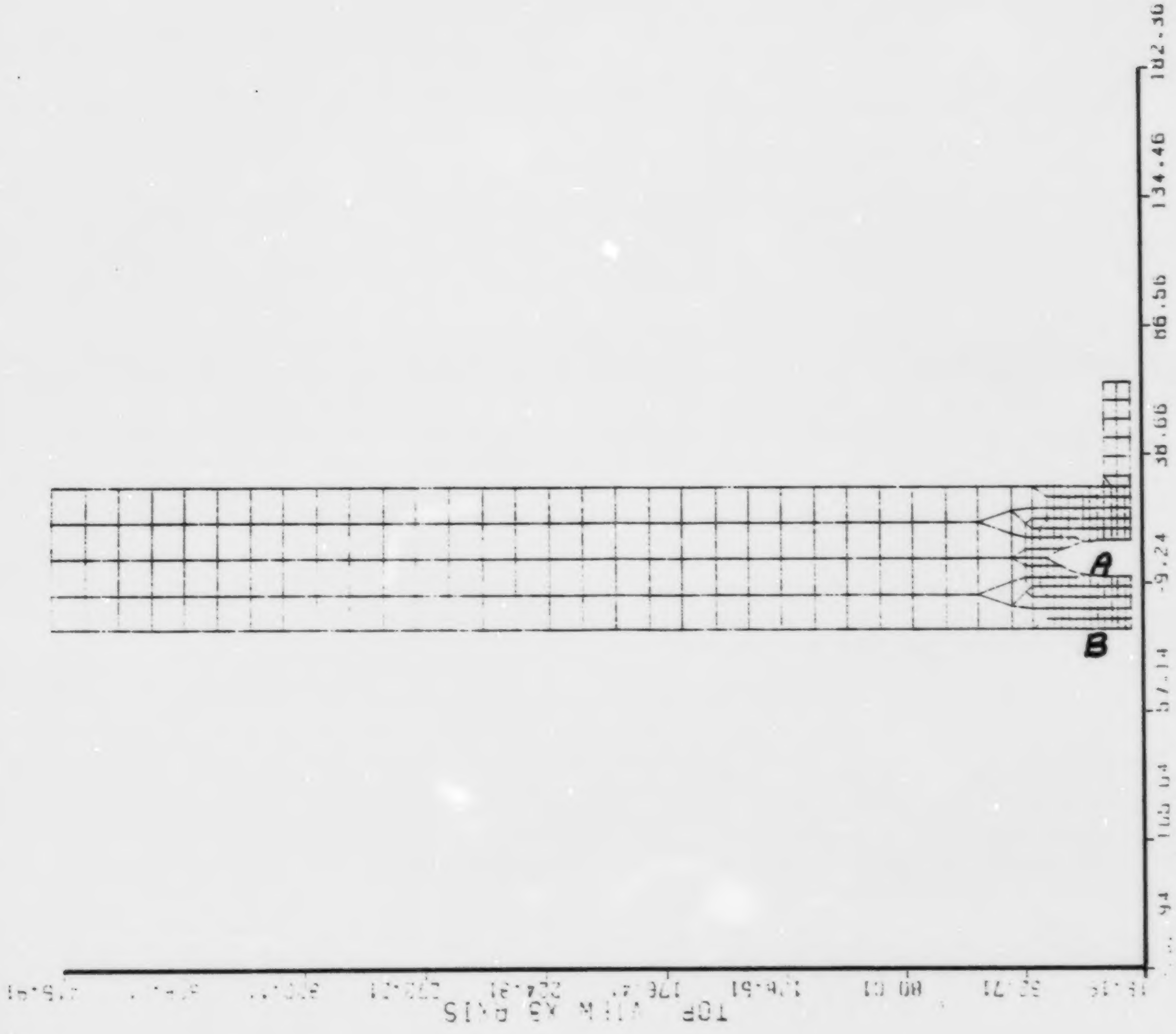

182.36
134.46
86.56
38.66
-9.24
-57.14
-105.04
A
B
TOP VIEW X3 AXIS

FIGURE 2
NORMAL LOAD ASSUMING RIGID DOCK FOUNDATION

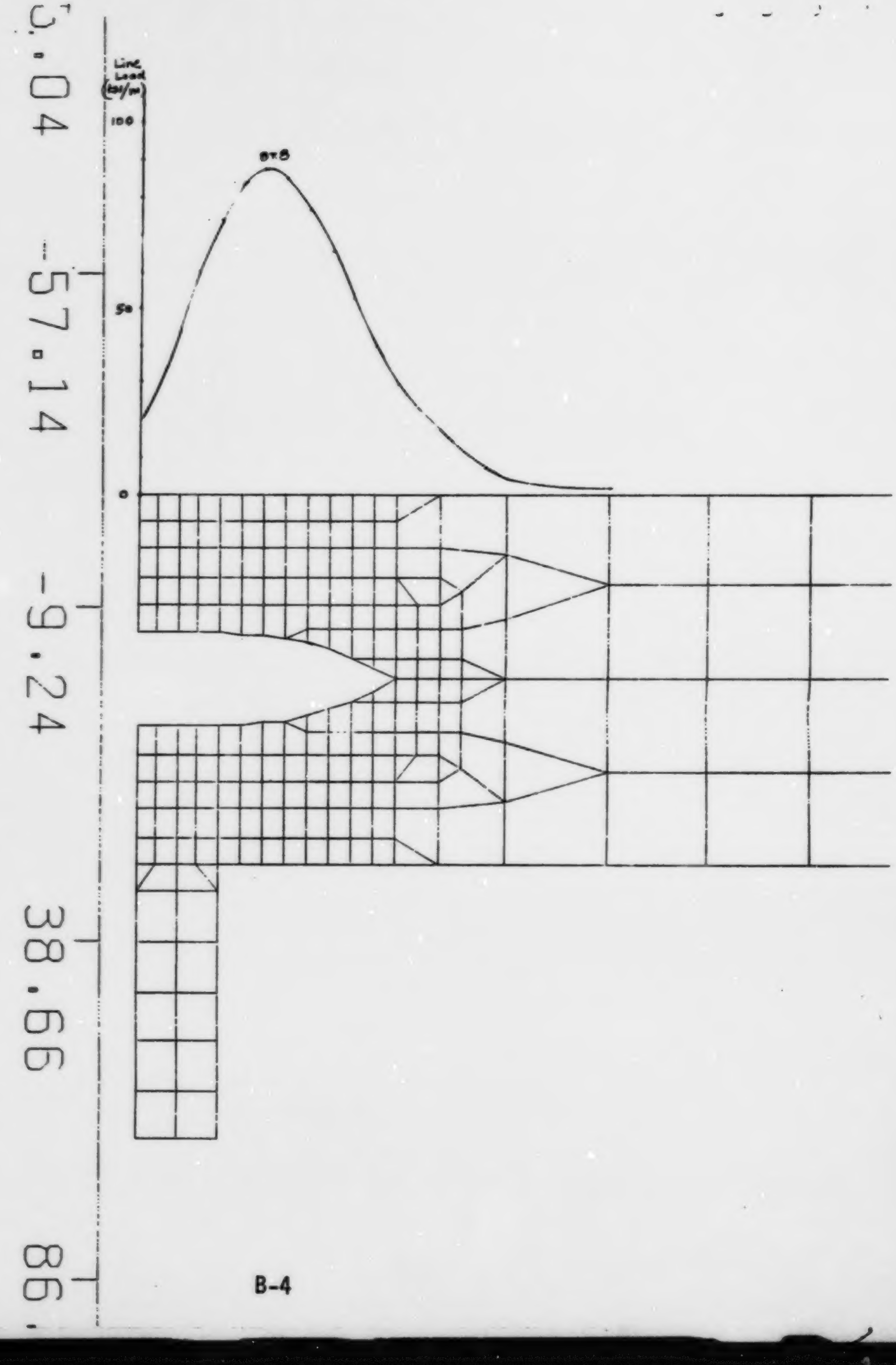
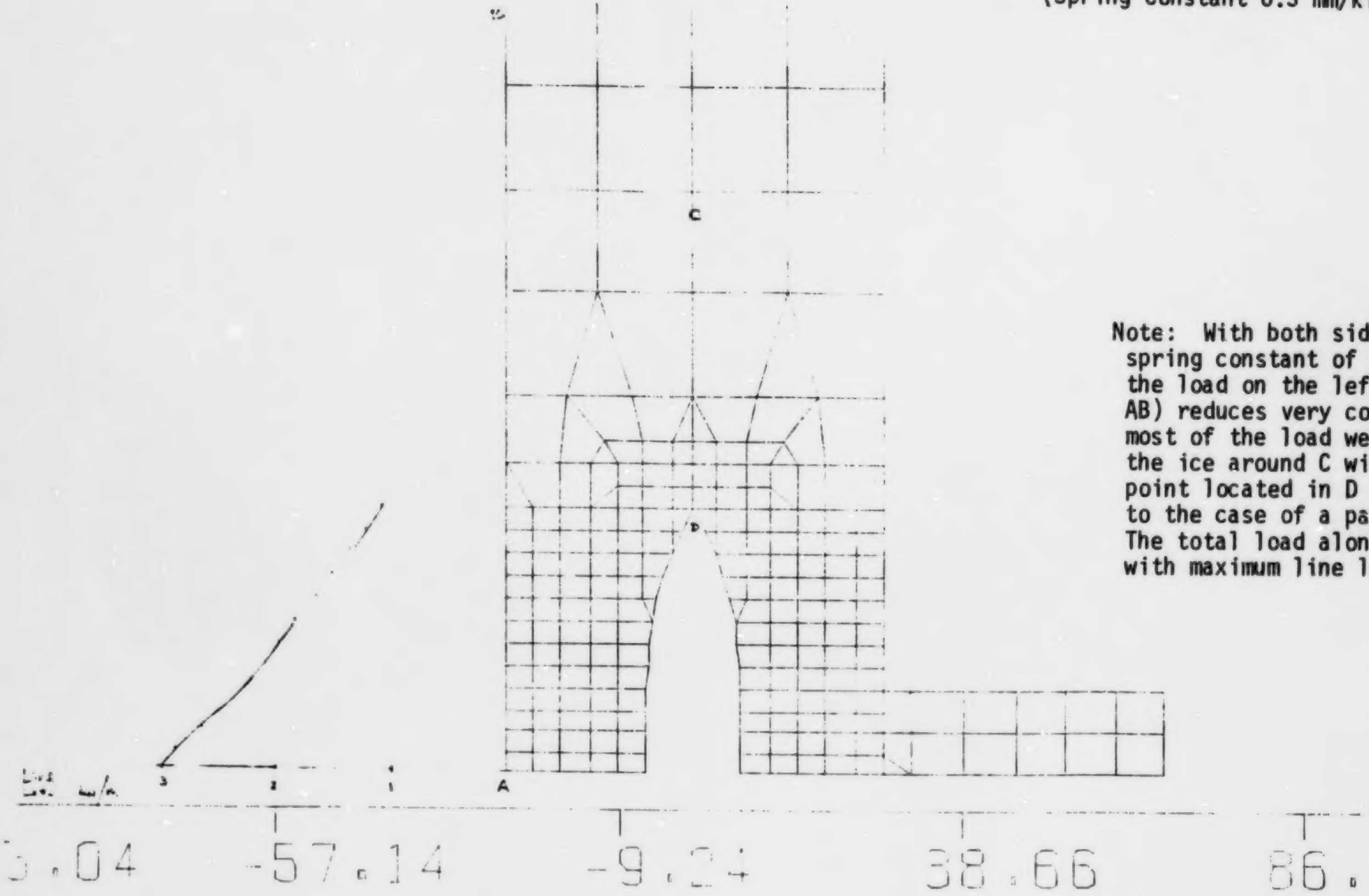

Line Load
100
87.8
50
0
3.04
-57.14
-9.24
38.66
86.

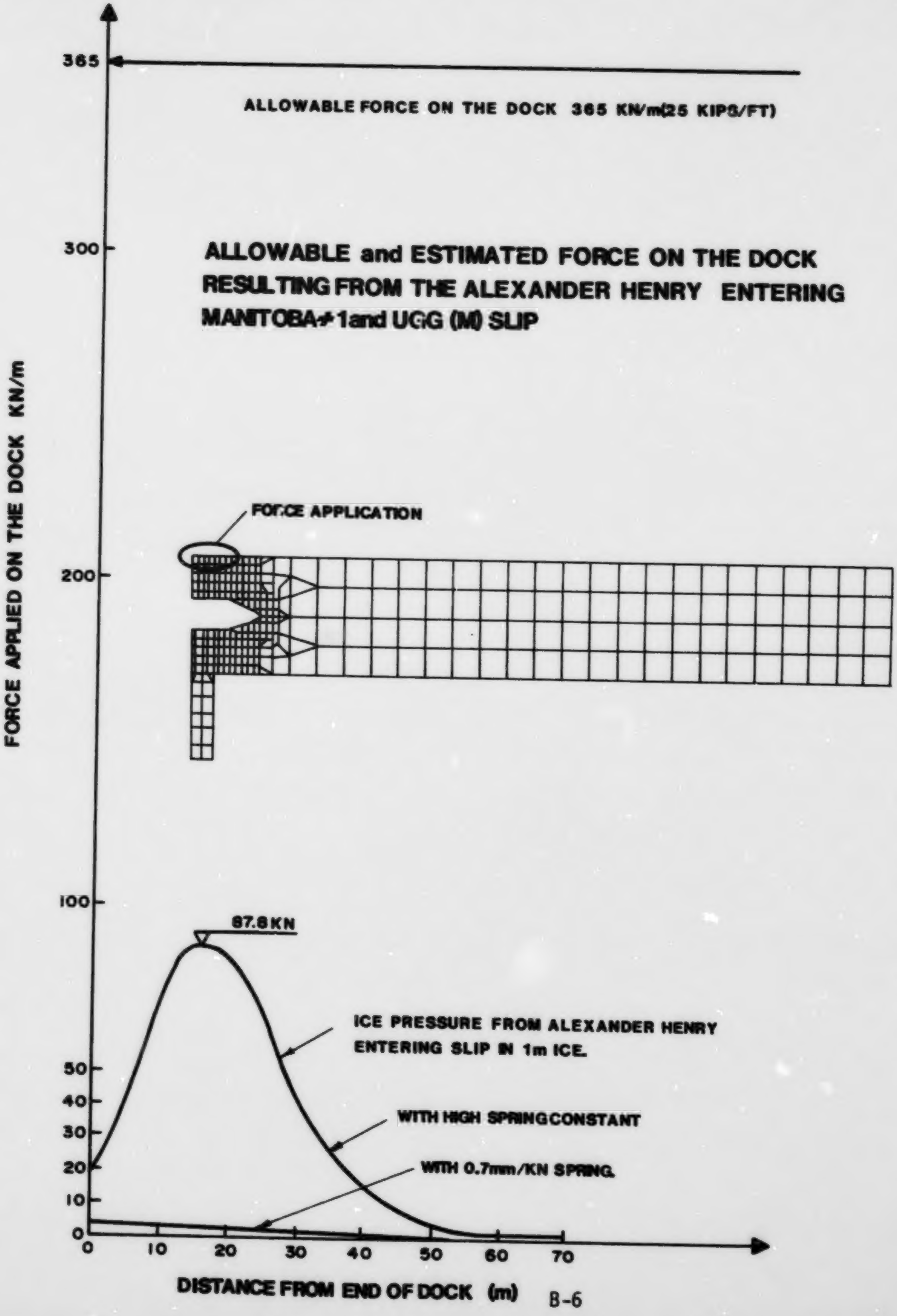
FIGURE 3

NORMAL LOAD ASSUMING FLEXIBLE FOUNDATION
(Spring Constant 0.3 mm/kips)



Note: With both sides having a spring constant of 0.3 mm/kip, the load on the left pier (along AB) reduces very considerably and most of the load were taken by the ice around C with pivot point located in D (it is analogous to the case of a pair of scissors). The total load along AB was 74 Kn with maximum line load of ≅ 3 Kn/m.

FIGURE 4


365
ALLOWABLE FORCE ON THE DOCK 365 KN/m(25 KIPS/FT)
300
ALLOWABLE and ESTIMATED FORCE ON THE DOCK RESULTING FROM THE ALEXANDER HENRY ENTERING MANITOBA#1and UGG (M) SLIP
FORCE APPLICATION
200
100
87.8 KN
ICE PRESSURE FROM ALEXANDER HENRY ENTERING SLIP IN 1m ICE.
WITH HIGH SPRING CONSTANT
WITH 0.7mm/KN SPRING.
50
40
30
20
10
0
0
10
20
30
40
50
60
70
FORCE APPLIED ON THE DOCK KN/m
DISTANCE FROM END OF DOCK (m)

APPENDIX C

MOTION MEASUREMENT OF THE GRAIN ELEVATOR

ICEBREAKER - GRAIN ELEVATOR INTERACTION

Due to concern over the possibility of damage to the grain elevator and docking facilities as a result of nearby icebreaking activities, an analysis of the structures involved was carried out. Since the ice loading involved is a transient phenomenon, a dynamic analysis was deemed appropriate. In addition, the actual response of the grain elevator was to be monitored with an accelerometer.

A schematic elevation end view of the grain handling complex (Fig.1 & 1(a)shows that the main structure is an arrangement of reinforced concrete silos standing on large reinforced concrete mats supported by a large number of timber piles. Along one side and the end is a dock and on the other side a railroad trestle. The sub soil is essentially a weak sand which is retained on three sides by a curtain of sheet piling. The main structure was built in three separate sections, each separated by a two inch expansion joint as shown in Figure 1(b). Hence it was decided to isolate the end section (Storage #3) for analysis since that would be where the measurements take place. This is a valid step provided deflections along the interface with storage #2 do not exceed the thickness of the expansion joint.

For the purpose of this analysis the structure was assumed to be linear elastic. The use of a simple model such as a beam was precluded due to the eccentricity of the proposed loading and accelerometer measurement. Since ice loading takes place near the foundation level, a model which employed a rigid foundation might be overly conservative. With the main structural features being "walls" and "slabs" rather than "beams" and "columns", a three dimensional finite element structure

FIGURE 1: GRAIN ELEVATOR LOCATIONS

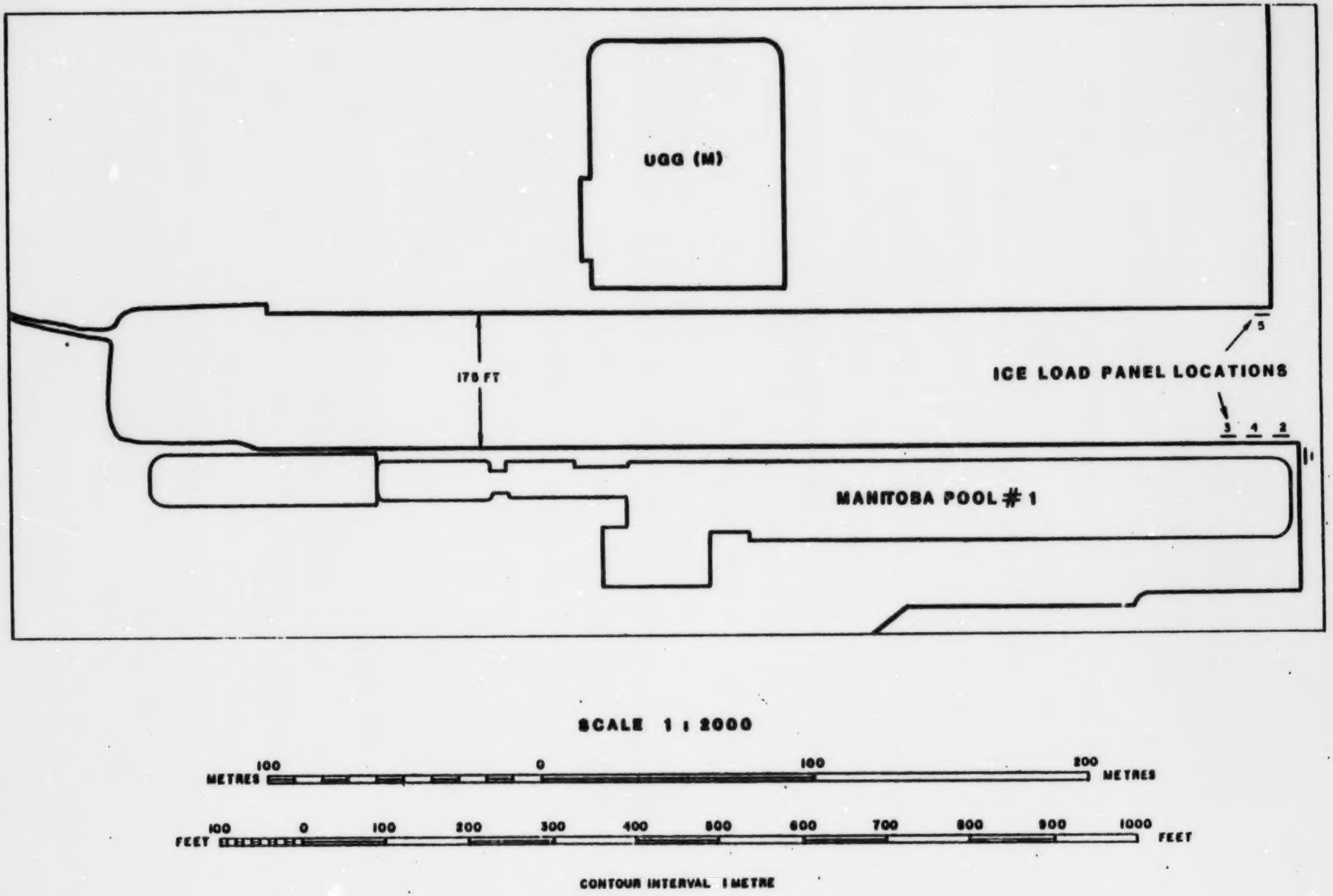

UGG (M)
175 FT
ICE LOAD PANEL LOCATIONS
5
3
4
2
1
MANITOBA POOL # 1
SCALE 1 : 2000
METRES
100
0
100
200
METRES
FEET
100
0
100
200
300
400
500
600
700
800
900
1000
FEET
CONTOUR INTERVAL 1 METRE

FIGURE 1(a) GRAIN ELEVATOR - TYPICAL CROSS SECTION

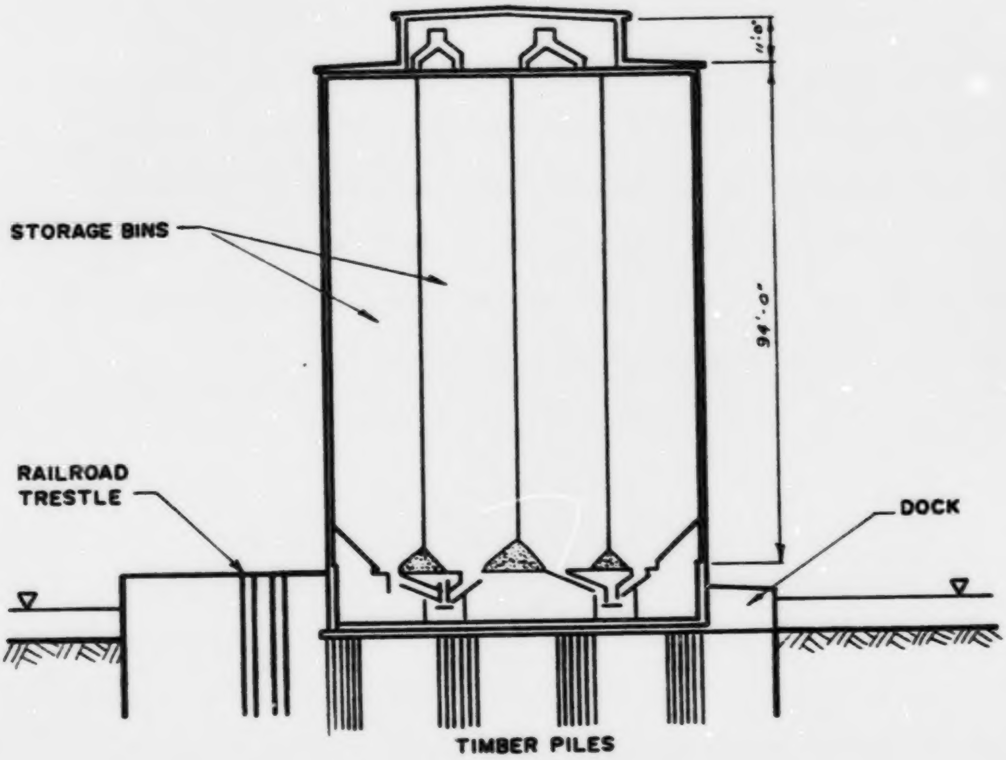
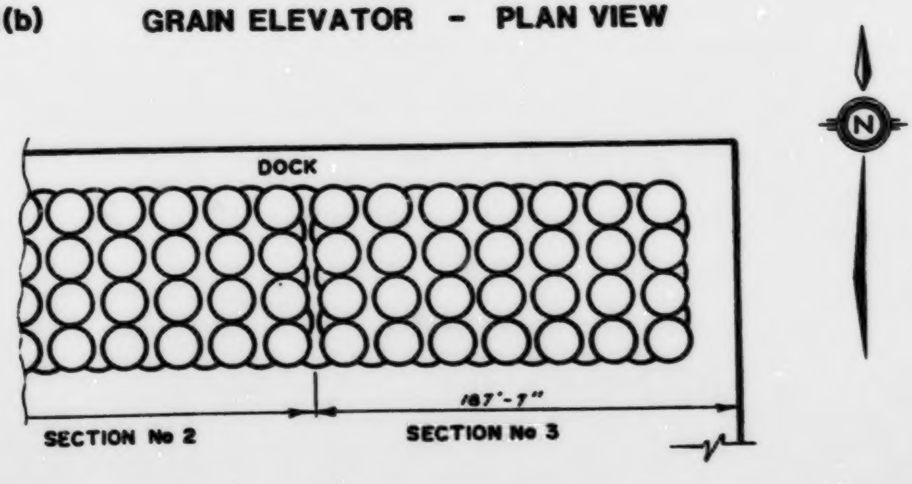

11'-0"
STORAGE BINS
94'-0"
RAILROAD TRESTLE
DOCK
TIMBER PILES

FIGURE 1(b) GRAIN ELEVATOR - PLAN VIEW


N
DOCK
187'-7"
SECTION No 2
SECTION No 3

(employing quadilateral plate elements) supported on an elastic foundation was proposed.

In order that the cost of analysis not be prohibitive, the structure was idealized into the form shown in Figure 2. The cross-sectional area of the bin walls of the model is roughly equivalent to that of all the silos in the actual structure. The internal structure of the basement has been idealized into two longitudinal walls. The overall dimensions and slab thicknesses for the remaining structural components are as in the working drawings. The following elastic properties of concrete are assumed:

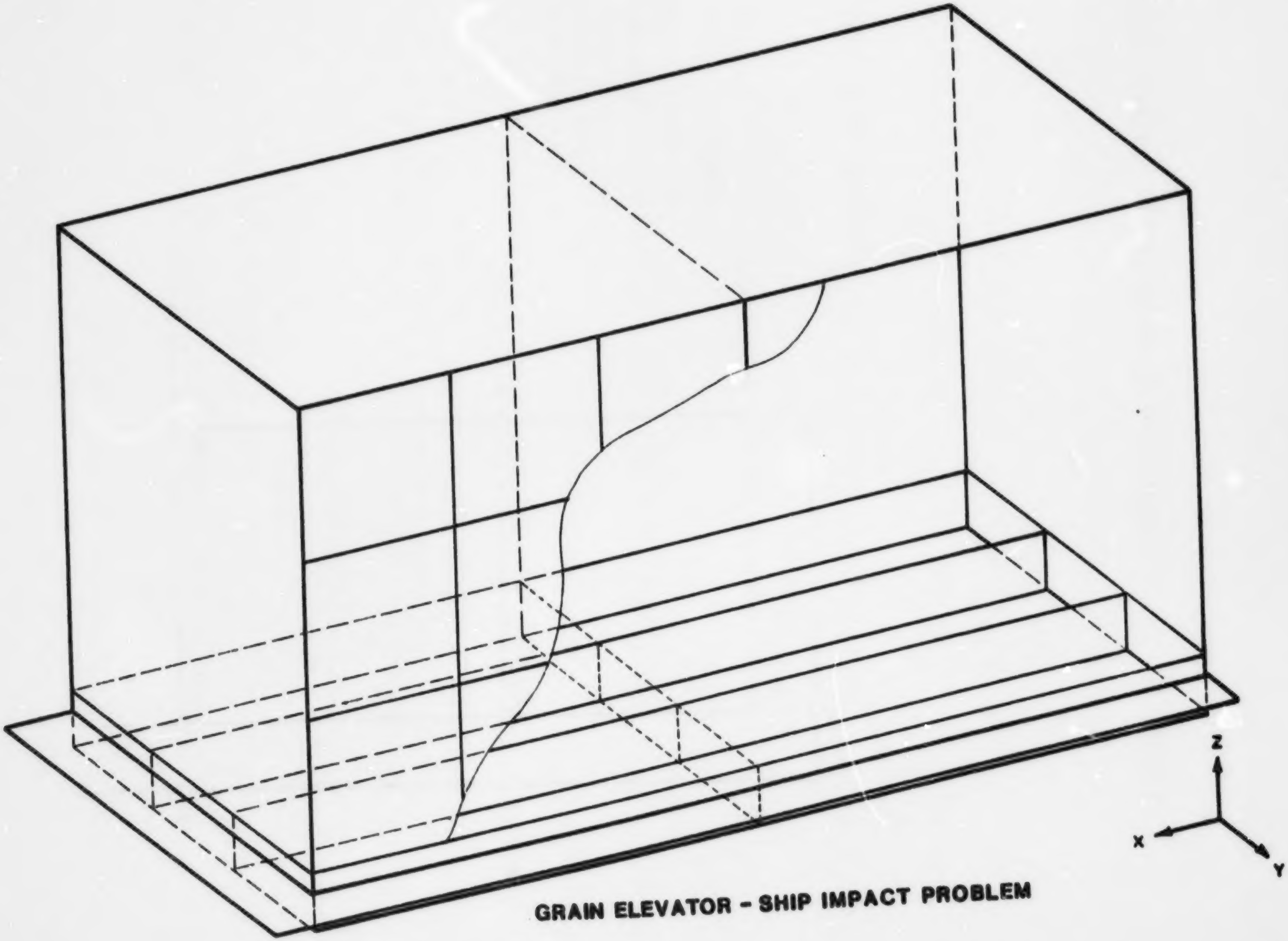
(i) $E_c = 4.749 \times 10^8$ psf
(ii) $\nu_c = 0.12$
(iii) $\rho_c = 150$ pcf

The foundation plan for the model is depicted in Figure 3. The piles have been lumped together at points on the base mat and along the dock face according to "tributary area". All piles are the same and the number at each location is indicated in brackets in the figure.

The stiffness constants for single piles (vertical, horizontal, torsional and rotation in vertical plane) may be calculated by formulae given by Novak (Reference 1 and 2). The required data consists of the geometry and material parameters of the pile and the shear wave velocity and material properties of the soil. In the present analysis the following assumptions were made:

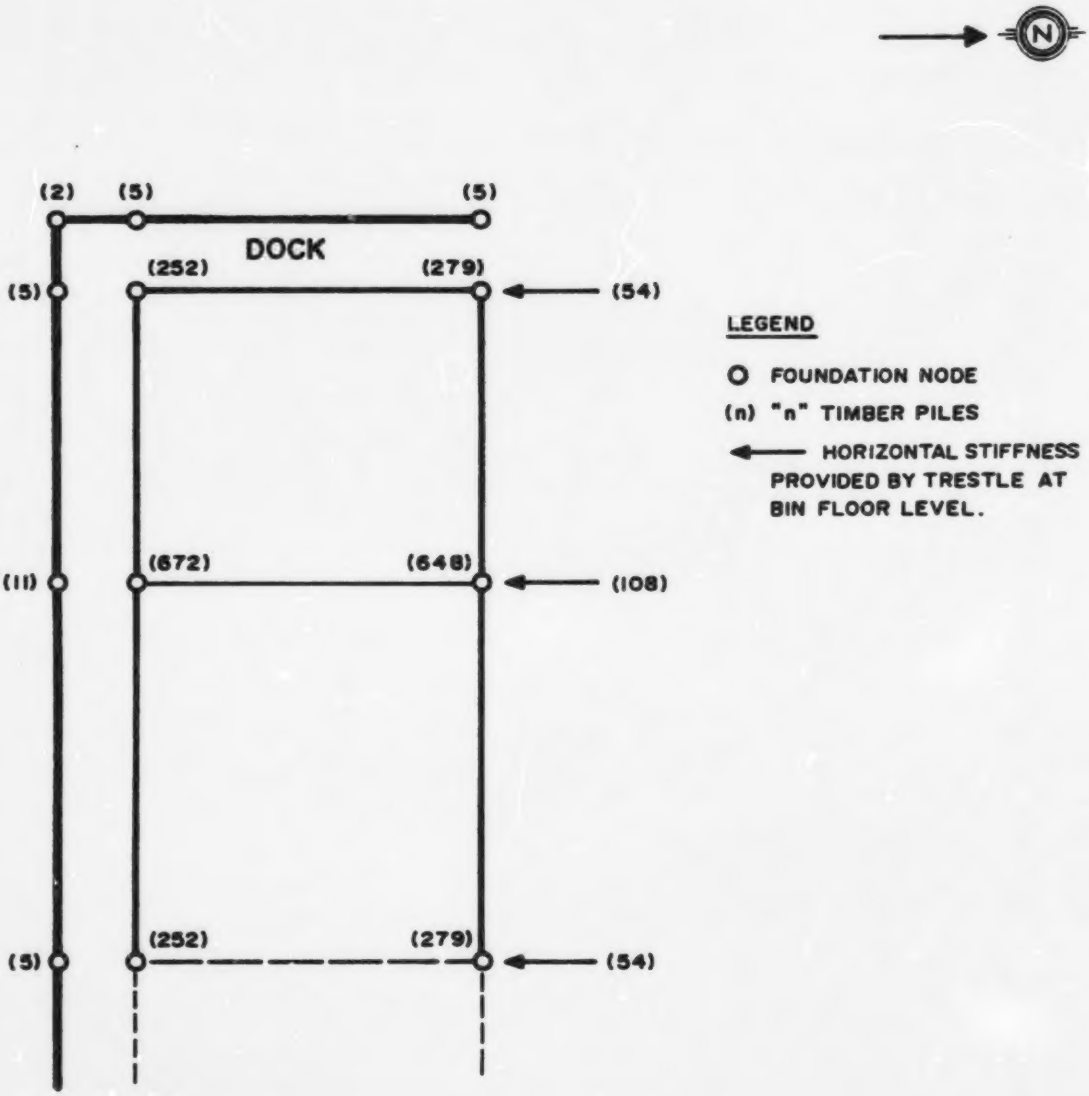
(i) 1 ft. diameter timber piles, 70 ft. long
(ii) soil density, $\phi = 115$ pcf
(iii) shear wave velocity, $v_s = 200$ ft/sec
(iv) Poisson's ratio $\nu_s = 0.25$

FIGURE 2 CUTAWAY VIEW OF FINITE ELEMENT MODEL OF STORAGE #3



GRAIN ELEVATOR - SHIP IMPACT PROBLEM

FIGURE 3 FOUNDATION PLAN OF FINITE ELEMENT MODEL


N
(2)
(5)
(5)
DOCK
(5)
(252)
(279)
(54)
(11)
(672)
(648)
(108)
(5)
(252)
(279)
(54)
LEGEND
O FOUNDATION NODE
(n) "n" TIMBER PILES
HORIZONTAL STIFFNESS PROVIDED BY TRESTLE AT BIN FLOOR LEVEL.

By summing the stiffnesses of the individual piles at each foundation point, the overall stiffnesses may be obtained.

The current model was analyzed using the STARDYNE group of finite element computer programs. With this software, structural response to dynamic loading is calculated by modal superposition. Modal damping of the structure as calculated by STARDYNE is based on a weighted average of strain energies in each component of the model. Five percent material damping was assumed for reinforced concrete.

In the present case the first ten natural frequencies and vibration modes were computed. The first and seventh structural mode are shown (for the dock side face of the storage bins) in Figures 4 (a) and (b). The natural frequencies and mass participation factors are indicated in Table 1. Note that for the loading cases under consideration here (i.e. transverse), the first and seventh modes are dominant. Since the ice loadings on the dock were expected to occur at relatively low frequencies, these first ten modes were considered sufficient for the present analysis.

FIGURE 4(a) DOCK FACE OF STORAGE - 1st VIBRATION MODE

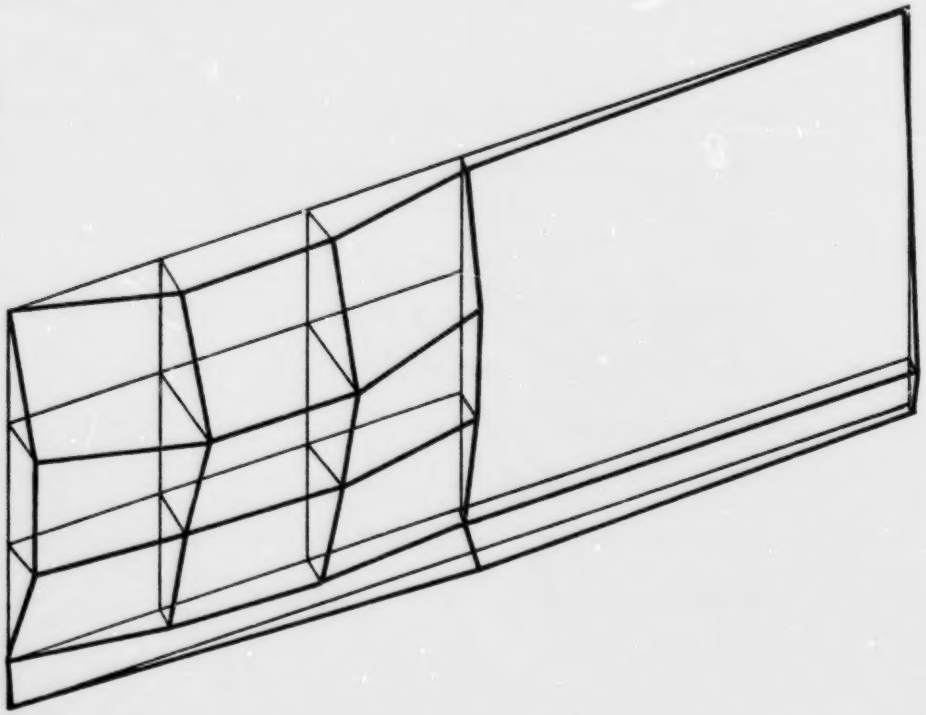


FIGURE 4(b) 7th VIBRATION MODE

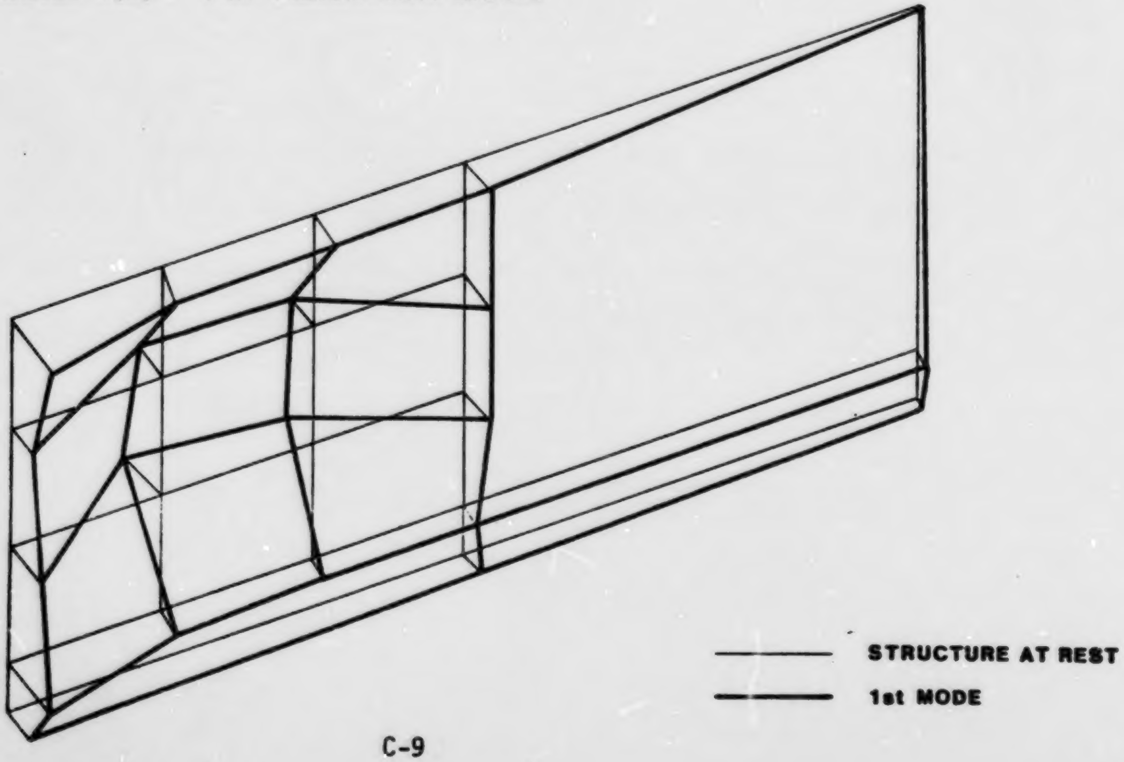

STRUCTURE AT REST
1st MODE

TABLE 1: NATURAL FREQUENCIES AND MASS PARTICIPATION FACTOR

MODE	NATURAL FREQUENCIES (HZ)	GENERALIZED MASS PARTICIPATION		
		LENGTH WISE (x)	TRANSVERSE (y)	VERTICAL (z)
1	1.019	s	1.58	s
2	1.851	s	.517	s
3	1.967	s	.33	s
4	1.983	s	.27	s
5	2.379	.38	s	s
6	2.442	s	.32	s
7	2.540	s	1.28	s
8	3.441	s	.11	s
9	3.599	s	.58	s
10	3.946	s	s	s

Note: "s" denotes less than 0.1

For the purposes of this study, the collision of an icebreaking vessel with the corner of the dock might be considered a worst case loading scenario. This is depicted in Figure 5. The dynamic load on the dock may be considered to be pulse of short duration which is in turn equivalent to a resultant change in momentum (by definition) of the dock and attached grain storage structure. In equation form,

$$\int_{0}^{t_p} P(t)dt = M_{el}V_{el} \qquad \text{(Equation 1)}$$

where M_{el} and V_{el} are the mass and velocity after collision respectively of the grain storage structure. By conservation of momentum and use of the Newton's concept of velocity restitution one can derive:

$$V_{el} = (1 + k_r) \frac{M_s}{M_s + M_{el}} V_s \qquad \text{(Equation 2)}$$

where M_s and V_s are the mass and velocity before collision of the ship and k_r is the velocity restitution coefficient. The restitution coefficient ranges from zero (plastic collision) to one (elastic collision). Since the time history of a pulse, P(t) acting during collision processes is not very well known it is often replaced for analysis purposes by an equivalent rectangular pulse, P_o, such that

$$P_o t_p = \int_{0}^{t_p} P(t)dt \qquad \text{(Equation 3)}$$

where t_p is the duration of the pulse. Combining equation 1 to 3 we have

$$P_o = \frac{1}{t_p}\left[M_{el}\,(1 + k_r)\,\frac{M_s}{M_{el} + M_s}\,V_s\right] \qquad \text{Equation 4}$$

$$= \frac{1}{t_p}\,(1 + k_r)\left[\frac{M_s}{1 + (\frac{M_s}{M_{el}})}\right] V_s$$

In the present case, the following data were assumed:

Ship - MV ALEXANDER HENRY

M_s - 3996 metric tonnes (2.736×10^5 slugs)

V_s - 5 knots (7.33 ft/sec)

M_{el} - 1.043×10^6 slugs

k_r - 0. (plastic collision)

t_p - .020

These data lead to a value of P_o of about 10^6 lb.

Using the above data, the displacement, velocity and acceleration time histories of the structural response were calculated for critical points on the structure over a one second time interval. The extreme responses at the point of impact and the accelerometer location are shown in Table 2.

From these results it can be seen that the accelerometer response for the actual ice loading will be quite small ($<58.4/386.4 = 0.15$g) where g is the acceleration due to gravity.

TABLE 2: MAXIMUM STRUCTURAL RESPONSE TO RECTANGULAR PULSE

LOCATION	DISPLACEMENT (INCH)	VELOCITY (in/sec)	ACCELERATION (in/sec²)
Point of Impact	0.38	6.51	308.4
Accelerometer Location	0.36	3.16	58.4

References

1. Novak, M., "Dynamic Stiffness and Damping of Piles", Canadian Geotechnical Journal, Volume 11, No.4, 1974, pp 574-598.

2. Novak, M. and Howell, J.F., "Torsional Vibration of Pile Foundations", Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 103, No.GT4, April 1977.

3. "Stardyne User Manual (Version 3)", System Development Corporation, Santa Monica, California, March 1978.

APPENDIX D

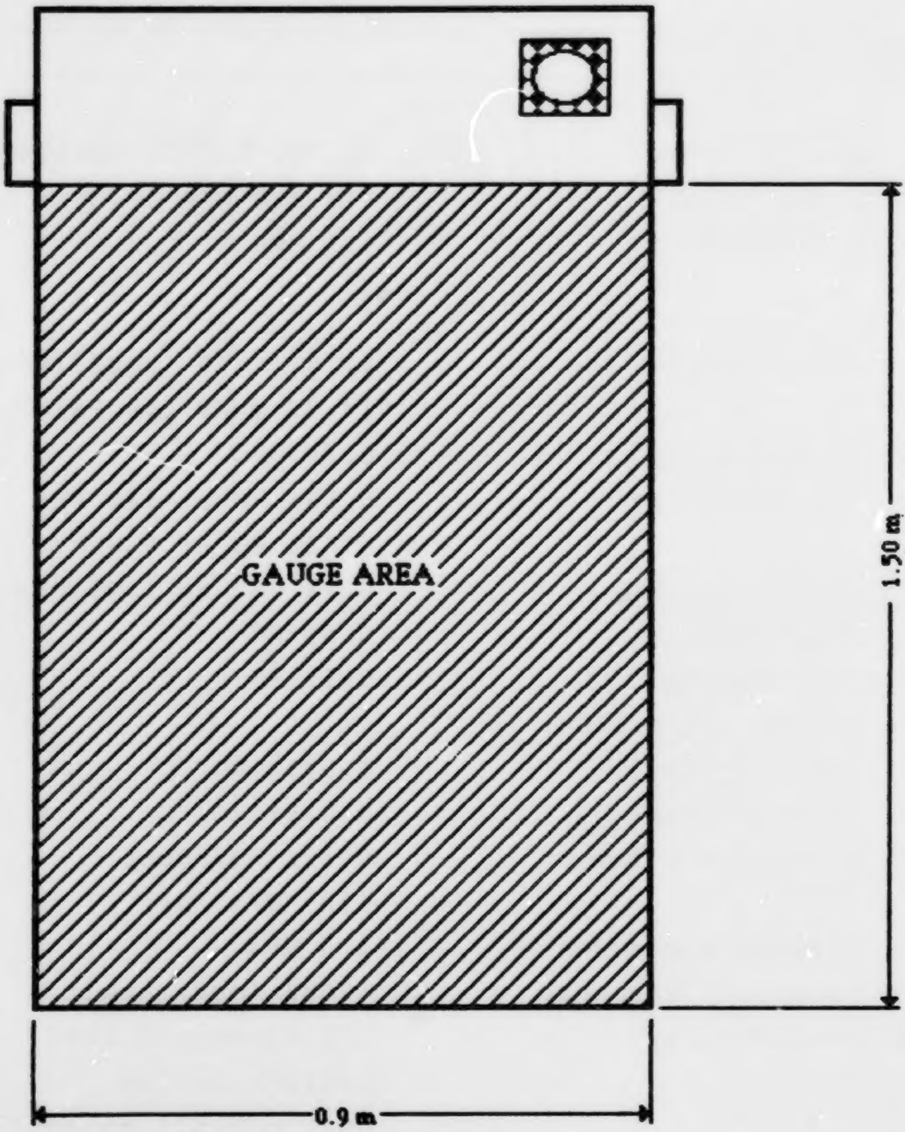
HEXPACK SPECIFICATIONS

HEXPACK SPECIFICATIONS

SPECIFICATION	
1. Manufacturer	ARCTEC CANADA LIMITED
2. Rating (R.O.)	0 - 2.8 MPa
3. Maximum Load	4.1 MPa
4. Sensitivity	1.164×10^{-3} mV/V/kPa [3.22 mV/V/2.8MPa]
5. Nonlinearity	0.34% RO
6. Repeatability	0.87% RO at 140 kPa 0.52% RO at 689 kPa 0.2% RO at 1300 kPa
7. Hysteresis	0.5% RO
8. Zero Return	0.1% RO
9. Thermal Stability:	
Zero Drift	0.049% RO/°C
Sensitibity	0.017% RO/°C
10. Creep Stability	0.12% RO/18hrs (187 N/m^2/hr)
11. Effective Modulus	1.5 GPa
12. Frequency Response	>20HZ (estimated)
13. Availability	All sizes and load ratings can be custom built to equal or better specs. than above.

HEXPACK DETAILS

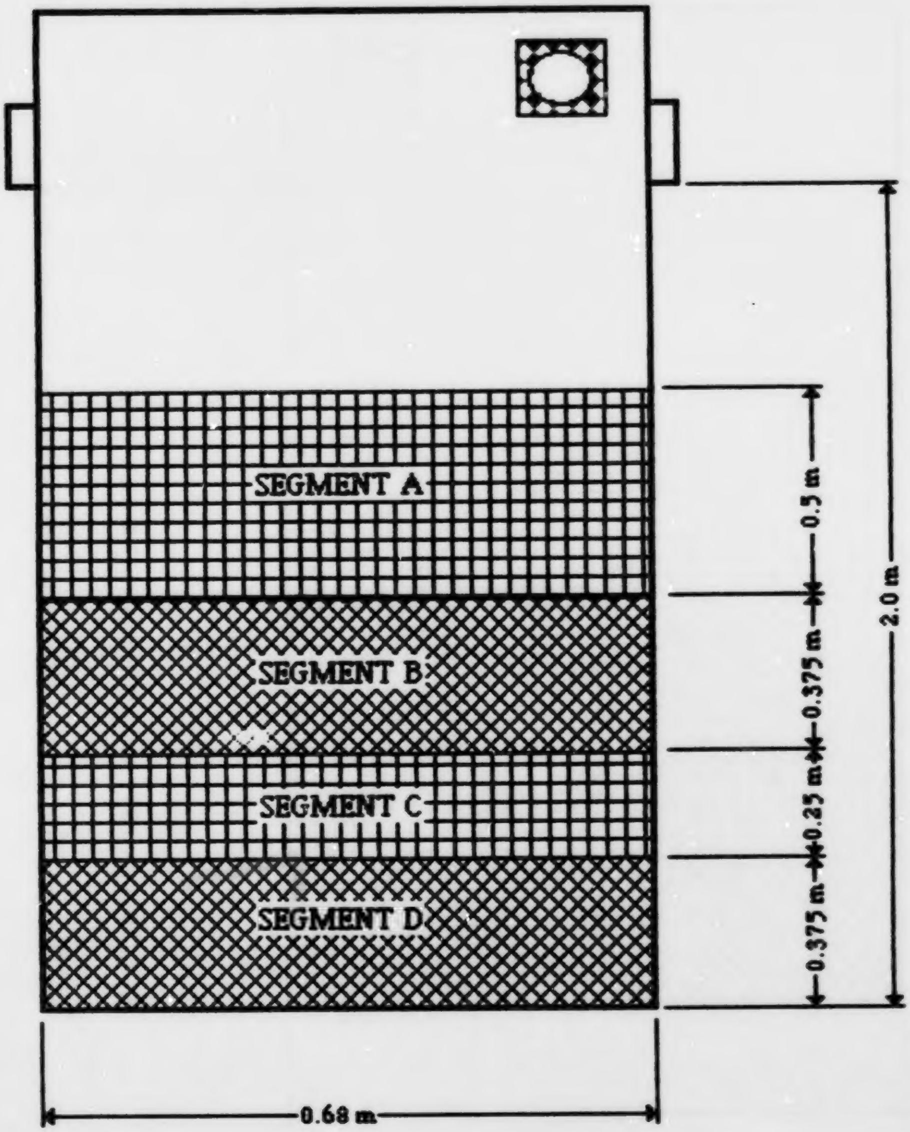
SERIAL NUMBER: 101
TYPE: AVERAGING


GAUGE AREA
1.50 m
0.9 m

CALIBRATION: 1.2354×10^{-3} mV/V/kPa

BEEPACK DETAILS

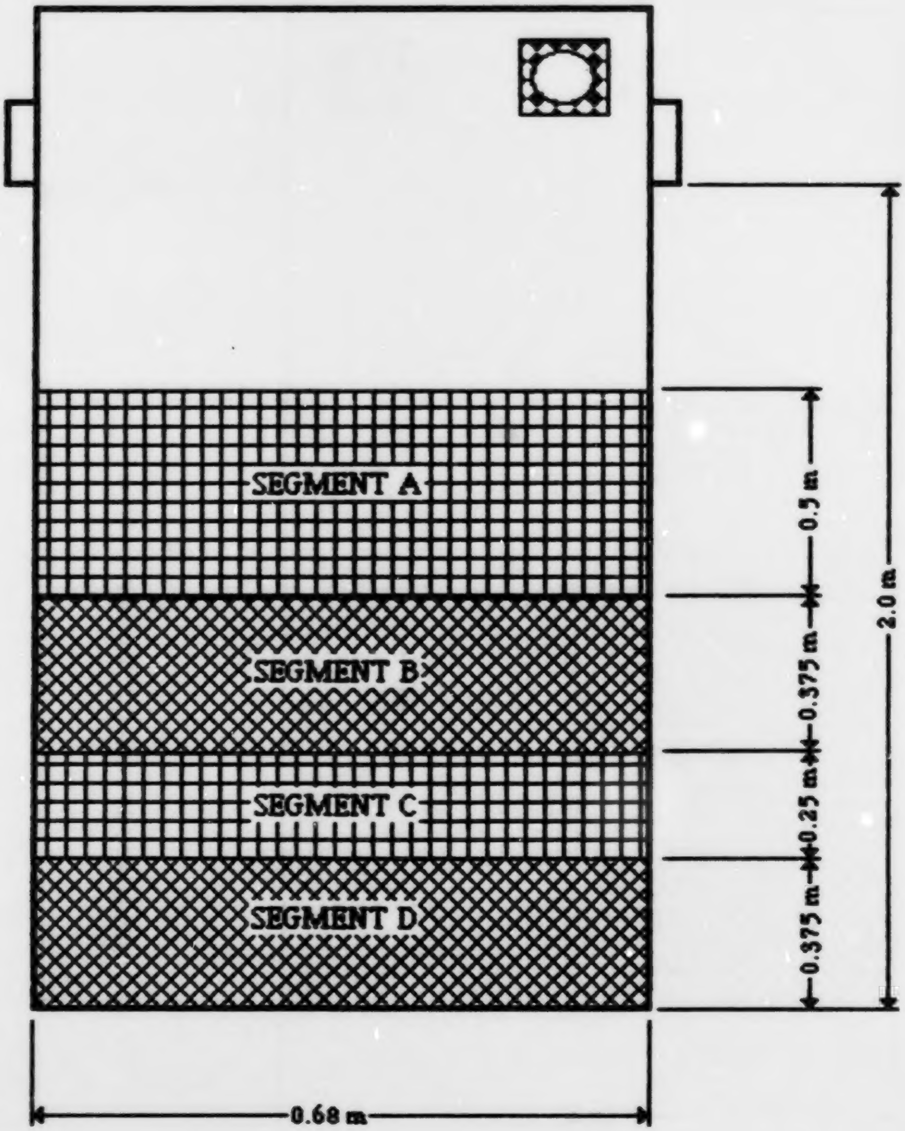
SERIAL NUMBER: 103
TYPE: SEGMENTED


SEGMENT A
SEGMENT B
SEGMENT C
SEGMENT D
0.5 m
0.375 m
0.25 m
0.375 m
2.0 m
0.68 m

CALIBRATION:	**Segment A**	1.0628×10^{-3} mV/V/kPa
	Segment B	1.1913×10^{-3} mV/V/kPa
	Segment C	1.0706×10^{-3} mV/V/kPa
	Segment D	9.5467×10^{-4} mV/V/kPa

MEDPACK DETAILS

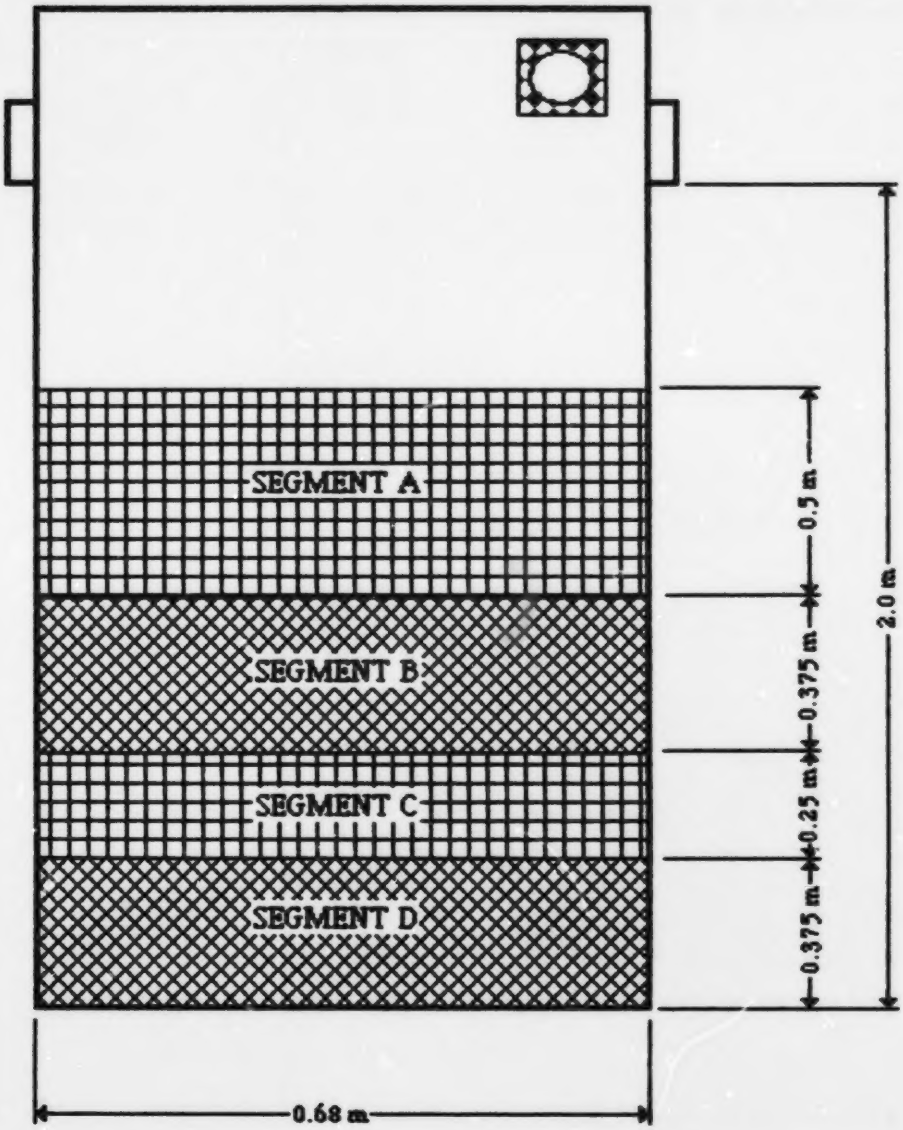
SERIAL NUMBER: 104
TYPE: SEGMENTED


SEGMENT A
SEGMENT B
SEGMENT C
SEGMENT D
0.5 m
0.375 m
0.25 m
0.375 m
2.0 m
0.68 m

CALIBRATION:	Segment A	9.8267×10^{-4} mV/V/kPa
	Segment B	1.0451×10^{-3} mV/V/kPa
	Segment C	1.1839×10^{-3} mV/V/kPa
	Segment D	9.3998×10^{-4} mV/V/kPa

BEEPACK DETAILS

SERIAL NUMBER: 105
TYPE: SEGMENTED

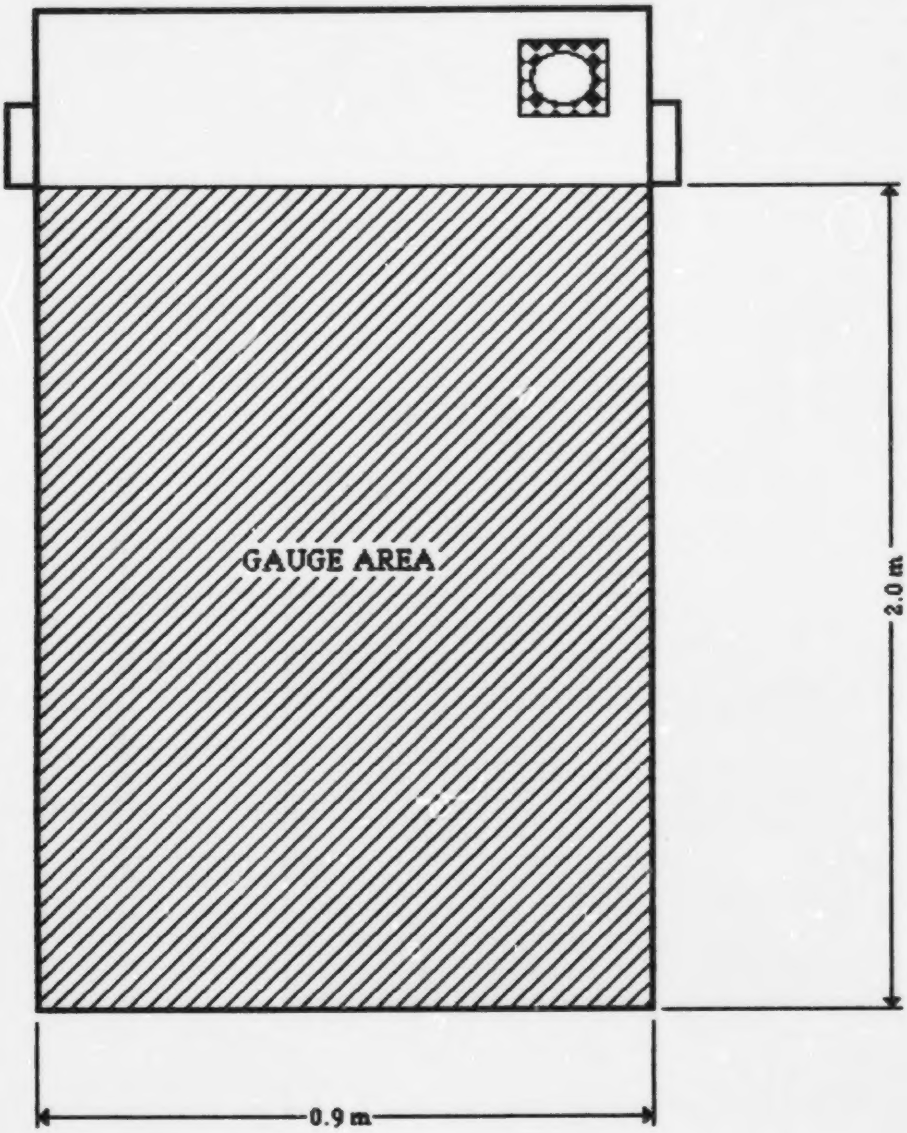

SEGMENT A
SEGMENT B
SEGMENT C
SEGMENT D
0.5 m
0.375 m
0.25 m
0.375 m
2.0 m
0.68 m

CALIBRATION:	Segment A	1.0023×10^{-3} mV/V/kPa
	Segment B	1.2396×10^{-3} mV/V/kPa
	Segment C	1.3284×10^{-3} mV/V/kPa
	Segment D	1.1019×10^{-3} mV/V/kPa

HEXPACK DETAILS

SERIAL NUMBER: 106

TYPE: AVERAGING


GAUGE AREA
2.0 m
0.9 m

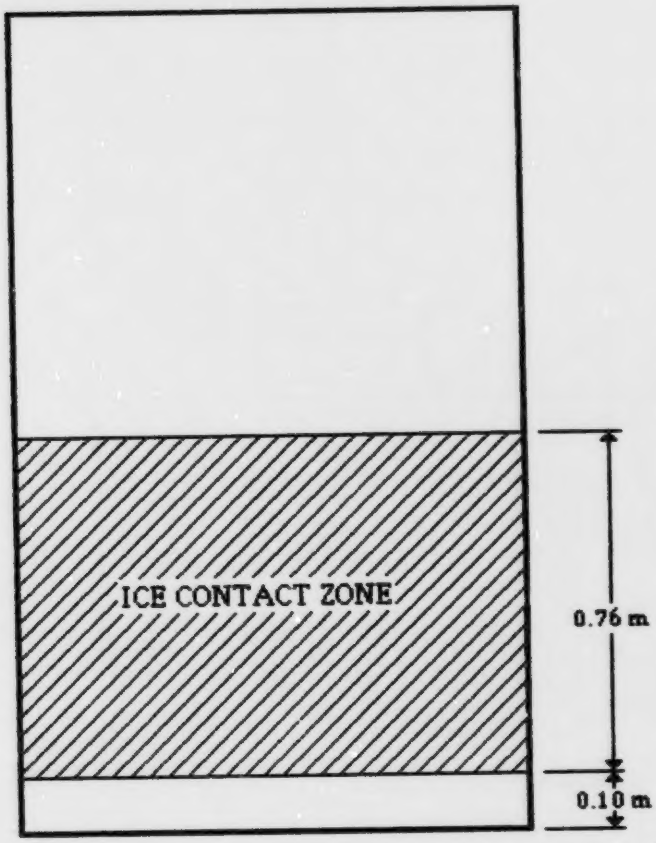
CALIBRATION: 1.2425×10^{-3} mV/V/kPa

APPENDIX E

DOCK LOAD CALCULATION

DOCK LOAD CALCULATION

HEXPACK SERIAL NUMBER: 101

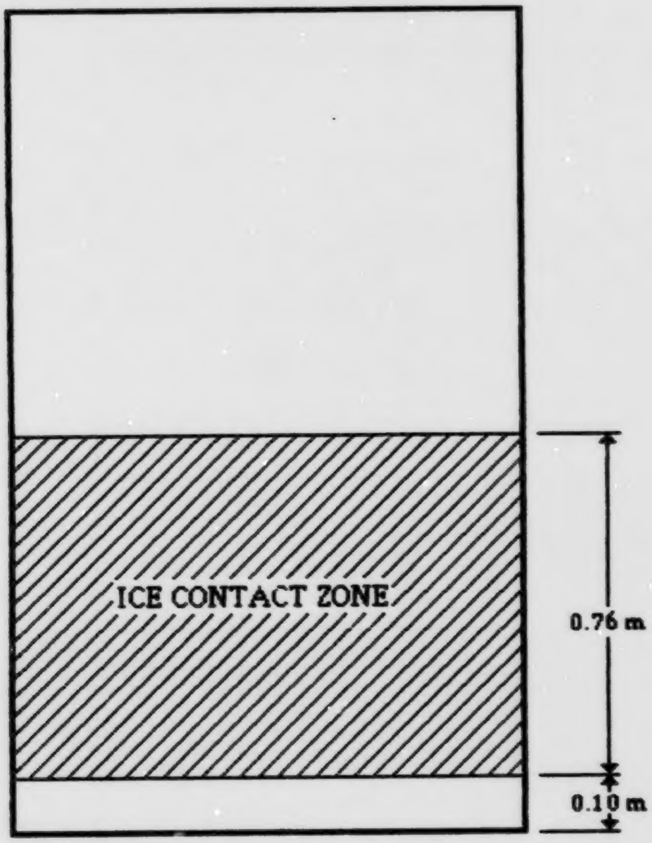

ICE CONTACT ZONE
0.76 m
0.10 m

P_{hex} = Hexpack Pressure (kPa)
F_i = Ice Force (kN/m)

$$\boxed{F_i = P_{hex} \times 1.5}$$

DOCK LOAD CALCULATION

HEXPACK SERIAL NUMBER: 103

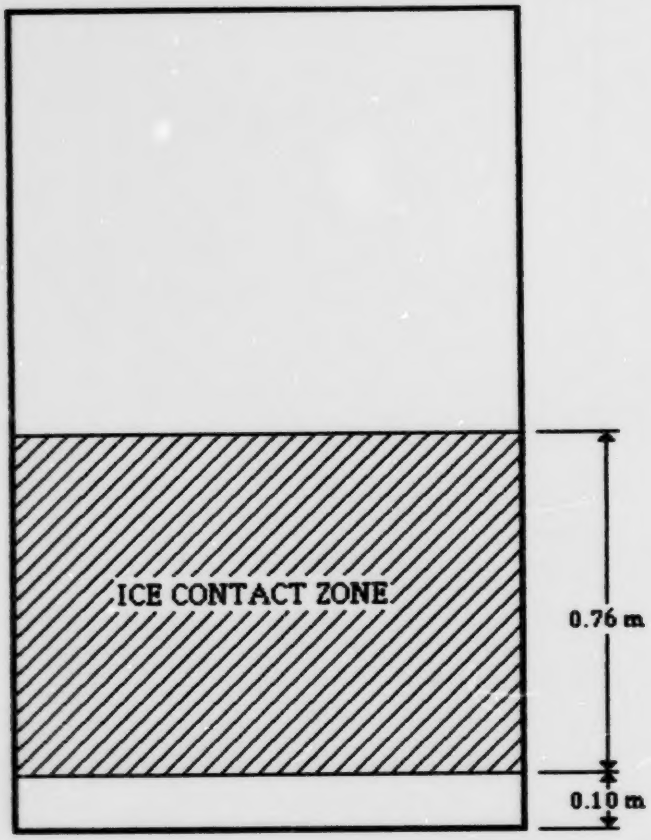


P_A = Hexpack Pressure Segment A (kPa)
P_B = Hexpack Pressure Segment B (kPa)
P_C = Hexpack Pressure Segment C (kPa)
P_D = Hexpack Pressure Segment D (kPa)
F_i = Ice Force (kN/m)

$$\boxed{F_i = P_A \times .5 + P_B \times .375 + P_C \times .25 + P_D \times .375}$$

DOCK LOAD CALCULATION

HEXPACK SERIAL NUMBER: 104

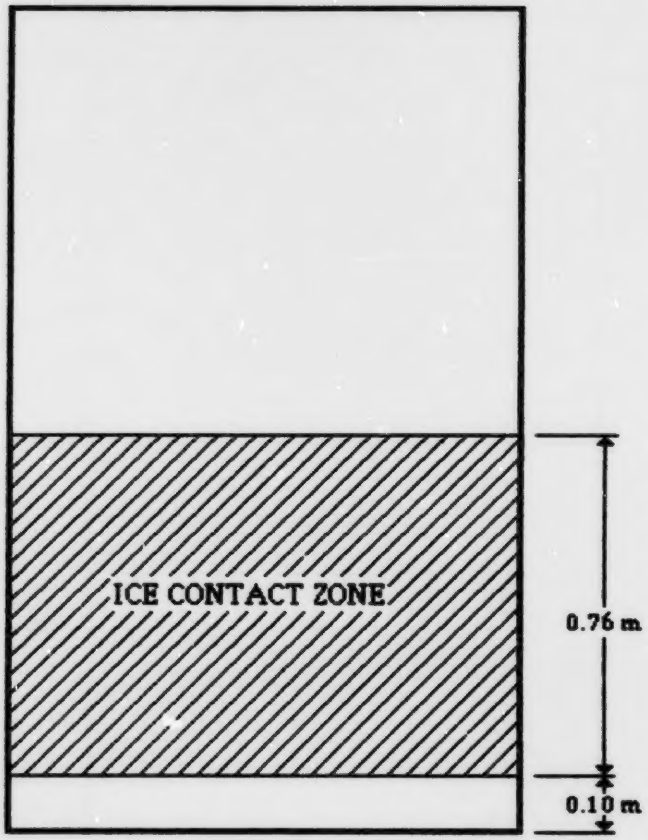


P_A = Hexpack Pressure Segment A (kPa)
P_B = Hexpack Pressure Segment B (kPa)
P_C = Hexpack Pressure Segment C (kPa)
P_D = Hexpack Pressure Segment D (kPa)
F_i = Ice Force (kN/m)

$$\boxed{F_i = P_A \times .5 + P_B \times .375 + P_C \times .25 + P_D \times .375}$$

DOCK LOAD CALCULATION

HEXPACK SERIAL NUMBER: 105

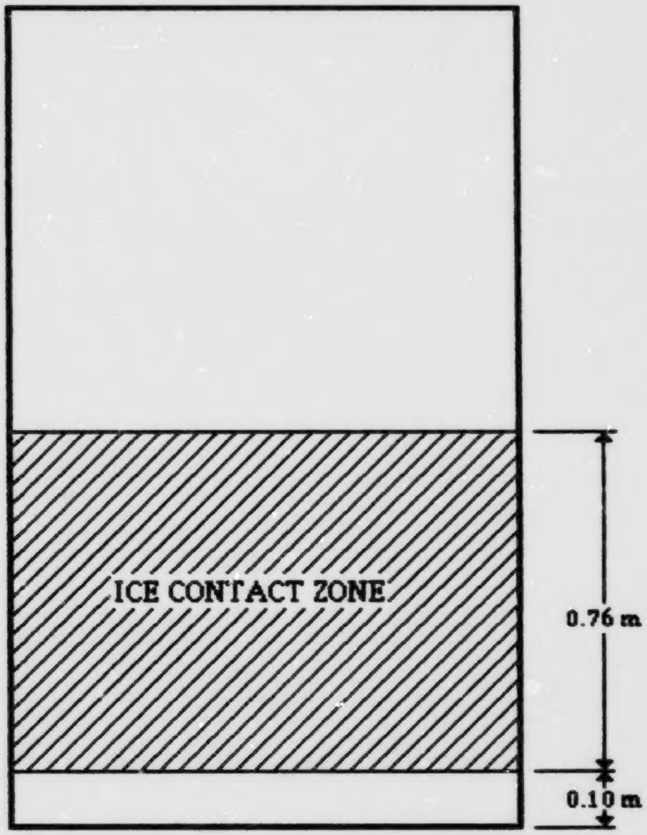


P_A = Hexpack Pressure Segment A (kPa)
P_B = Hexpack Pressure Segment B (kPa)
P_C = Hexpack Pressure Segment C (kPa)
P_D = Hexpack Pressure Segment D (kPa)
F_i = Ice Force (kN/m)

$$\boxed{F_i = P_A \times .5 + P_B \times .375 + P_C \times .25 + P_D \times .375}$$

DOCK LOAD CALCULATION

HEXPACK SERIAL NUMBER: 106


ICE CONTACT ZONE
0.76 m
0.10 m

P_{hex} = Hexpack Pressure (kPa)
F_i = Ice Force (kN/m)

$$\boxed{F_i = P_{hex} \times 2.0}$$

APPENDIX F

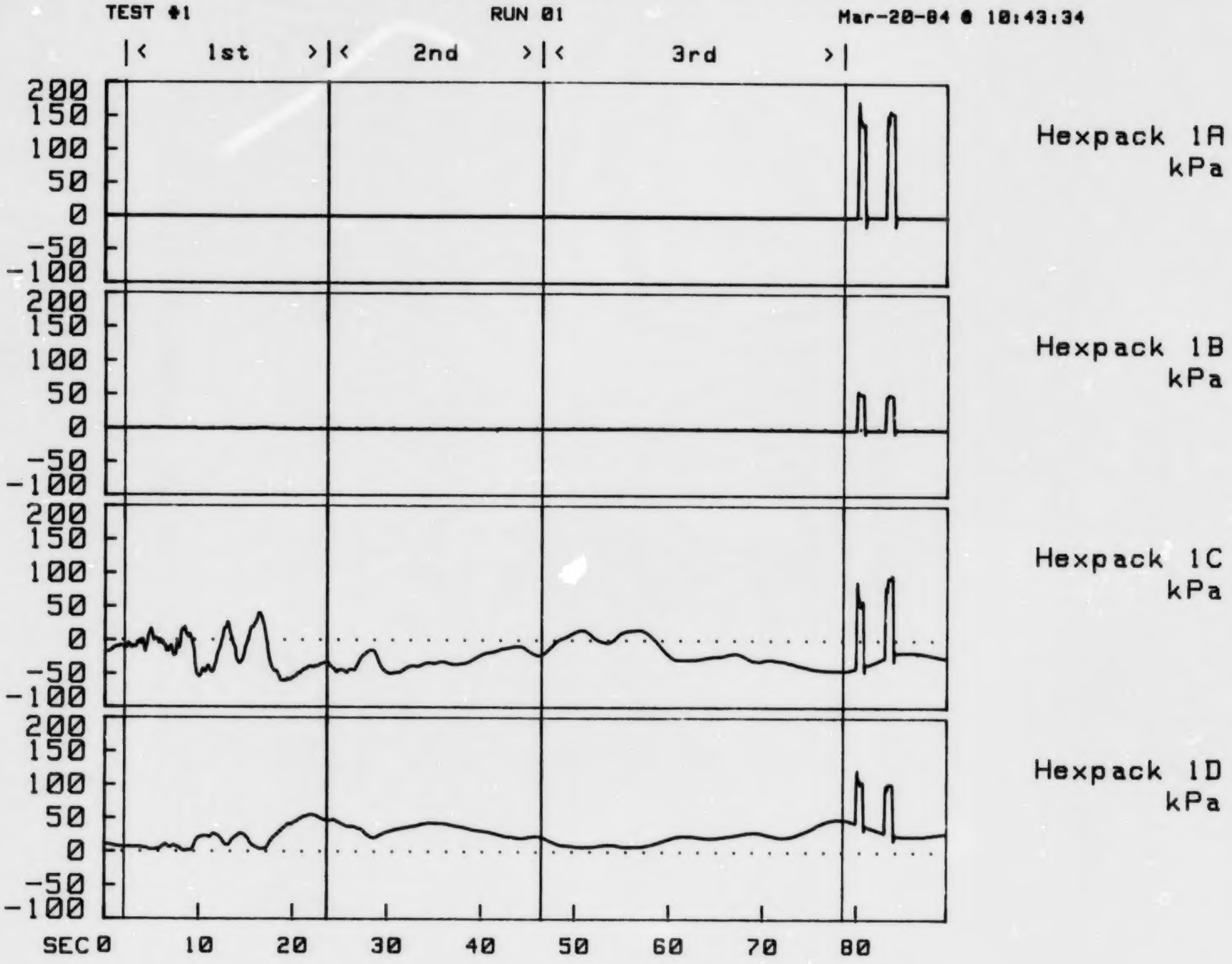
STATISTICS AND PLOTS OF RAW DATA

THUNDER BAY ICE LOAD TEST SUMMARY

Test #: 1
Run #: 01
Date: Mar-20-84
Scan Begins at: 10:43:34
Duration of Scan: 90 sec
Scan ends at: 10:45:04
Type of test: Alexander Henry
Location of Ship: 120 m E-S-E of dock
Ramming unbroken ice

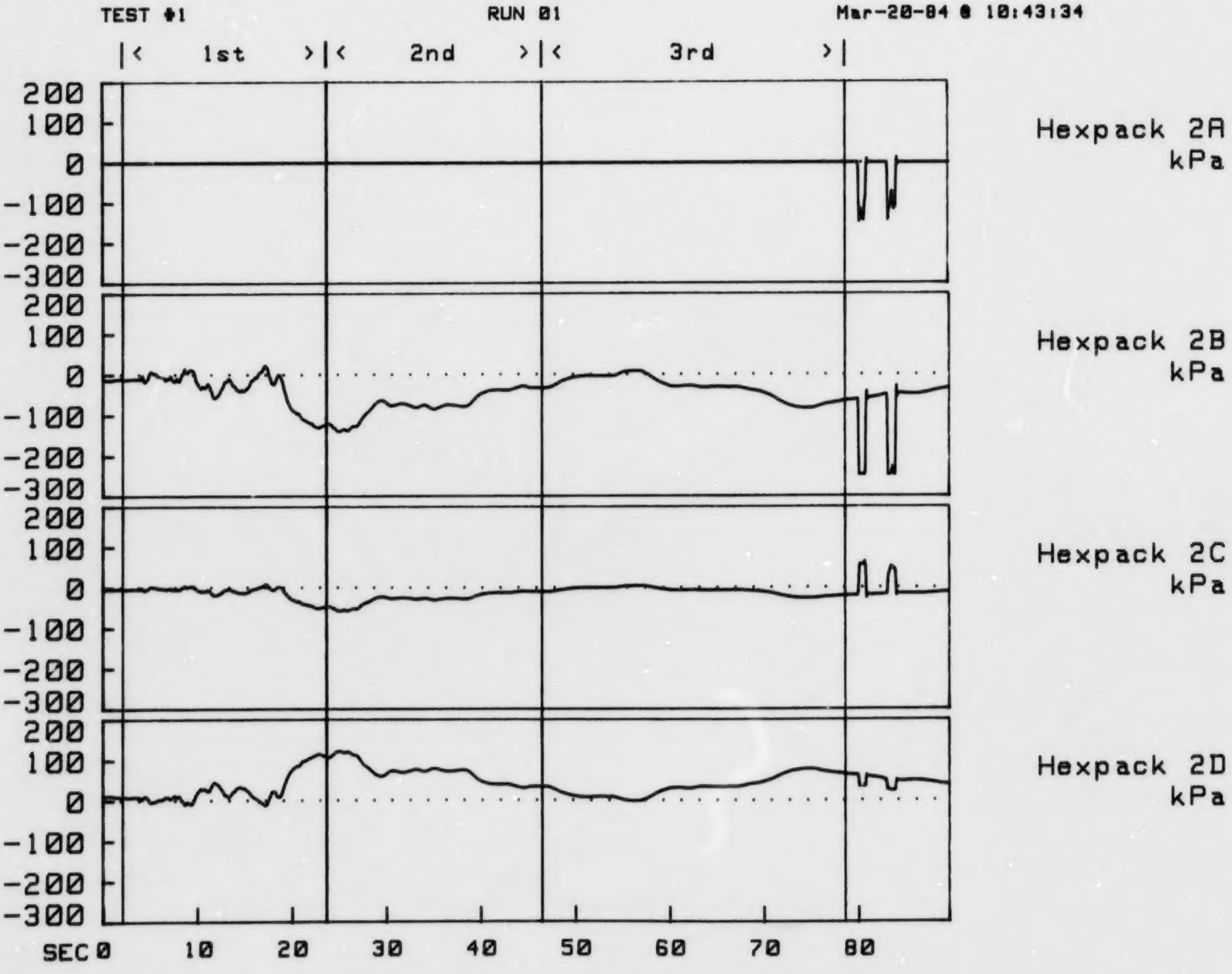
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	0.87	-0.58	kPa
Hex 1B	0.60	-4.41	kPa
Hex 1C	40.76	-60.91	kPa
Hex 1D	55.89	0.82	kPa
Hex 2A	0.72	-1.12	kPa
Hex 2B	23.19	-140.57	kPa
Hex 2C	8.28	-58.32	kPa
Hex 2D	123.16	-12.87	kPa
Hex 3A	1.21	-1.20	kPa
Hex 3B	36.57	-337.71	kPa
Hex 3C	33.30	-1.46	kPa
Hex 3D	177.31	-1.97	kPa
Hex 4	13.61	-2.70	kPa
Hex 5	64.12	-28.49	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	12.03	-6.78	kN/m
Hex 2 aver	5.89	-21.17	kN/m
Hex 3 aver	18.40	-60.16	kN/m
Hex 4 aver	27.23	-5.40	kN/m
Hex 5 aver	96.18	-42.73	kN/m

Comments: Two communication spikes after 80 sec.



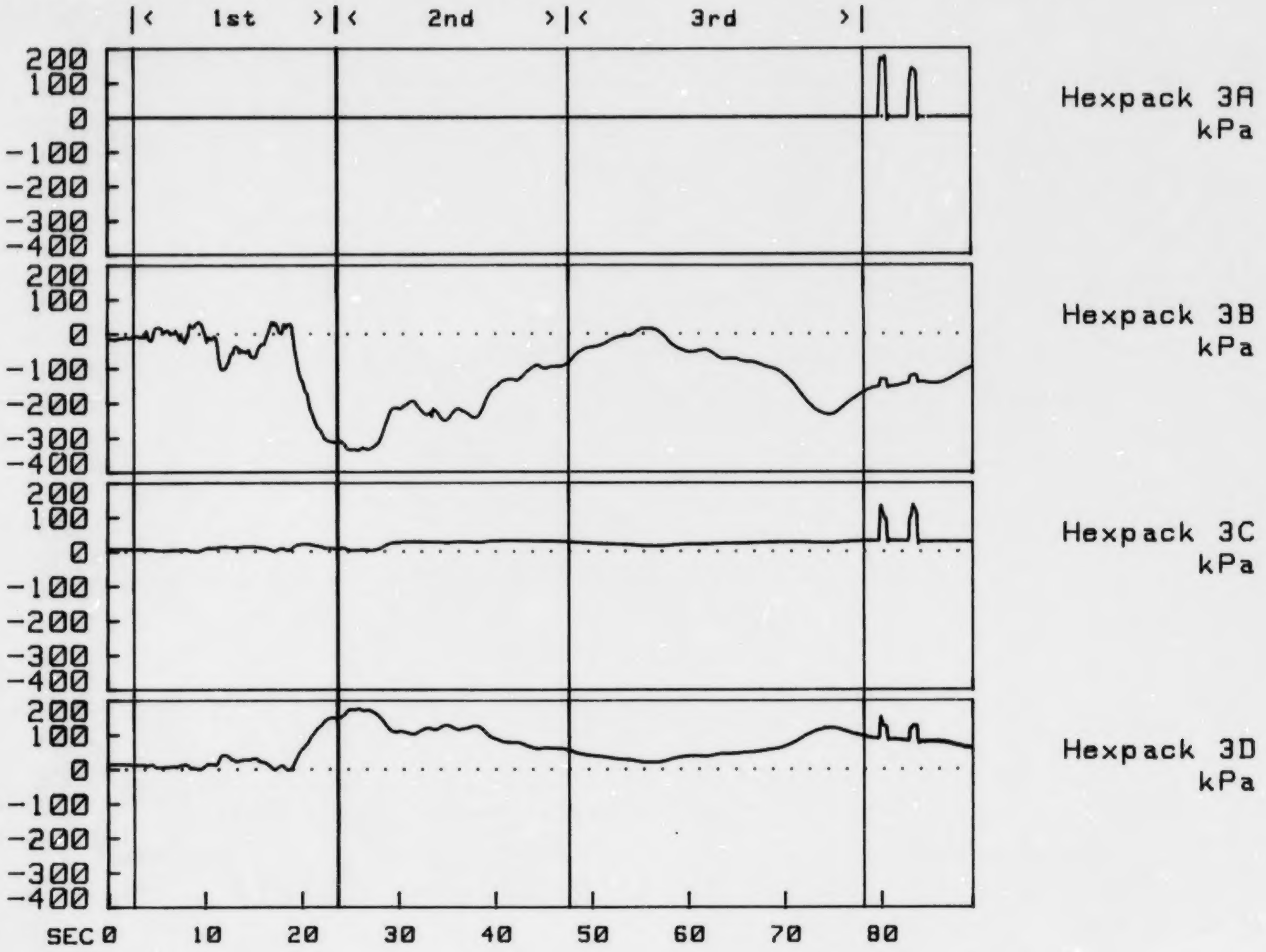
1371C Thunder Bay Ice Loads

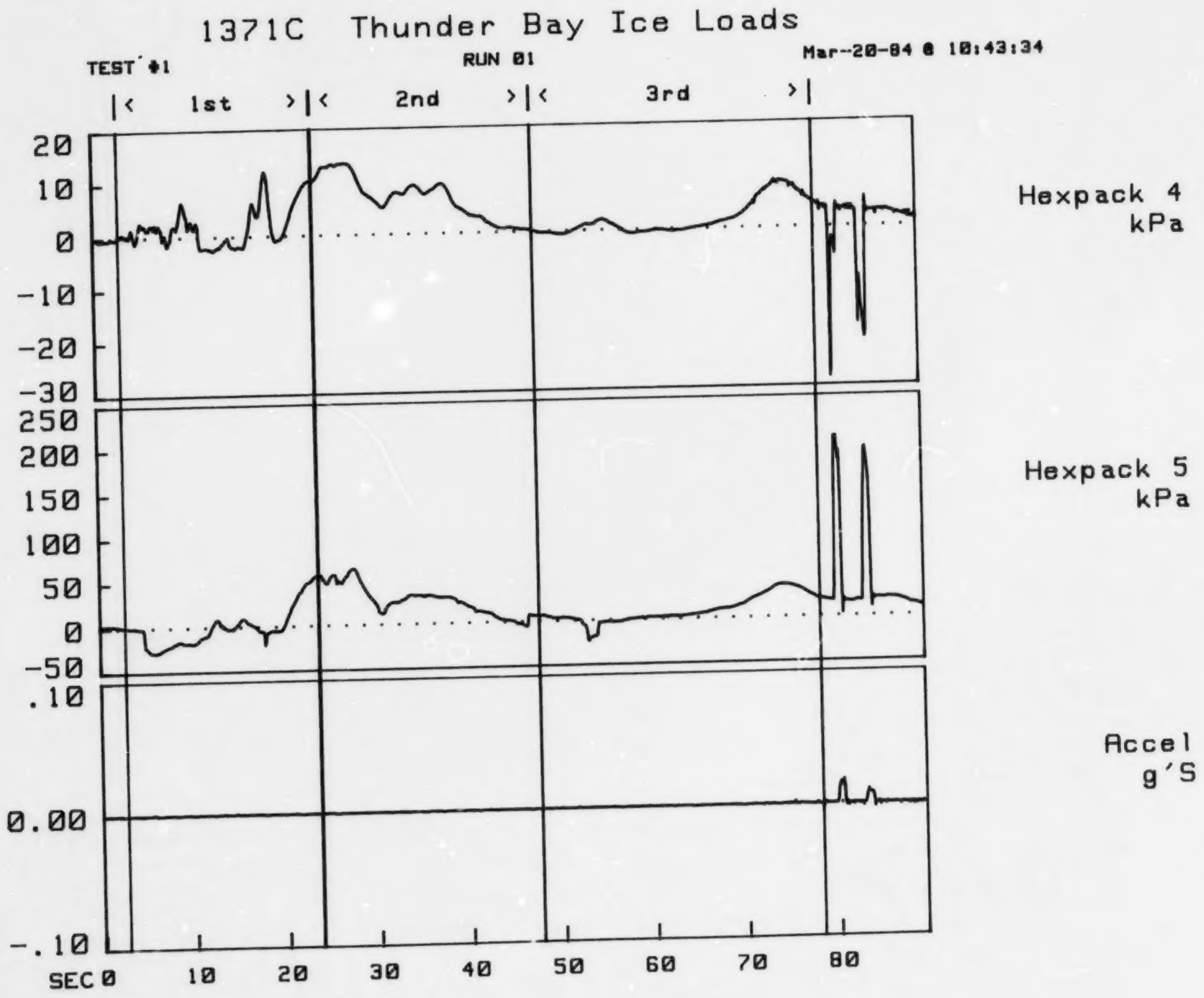
1371C Thunder Bay Ice Loads

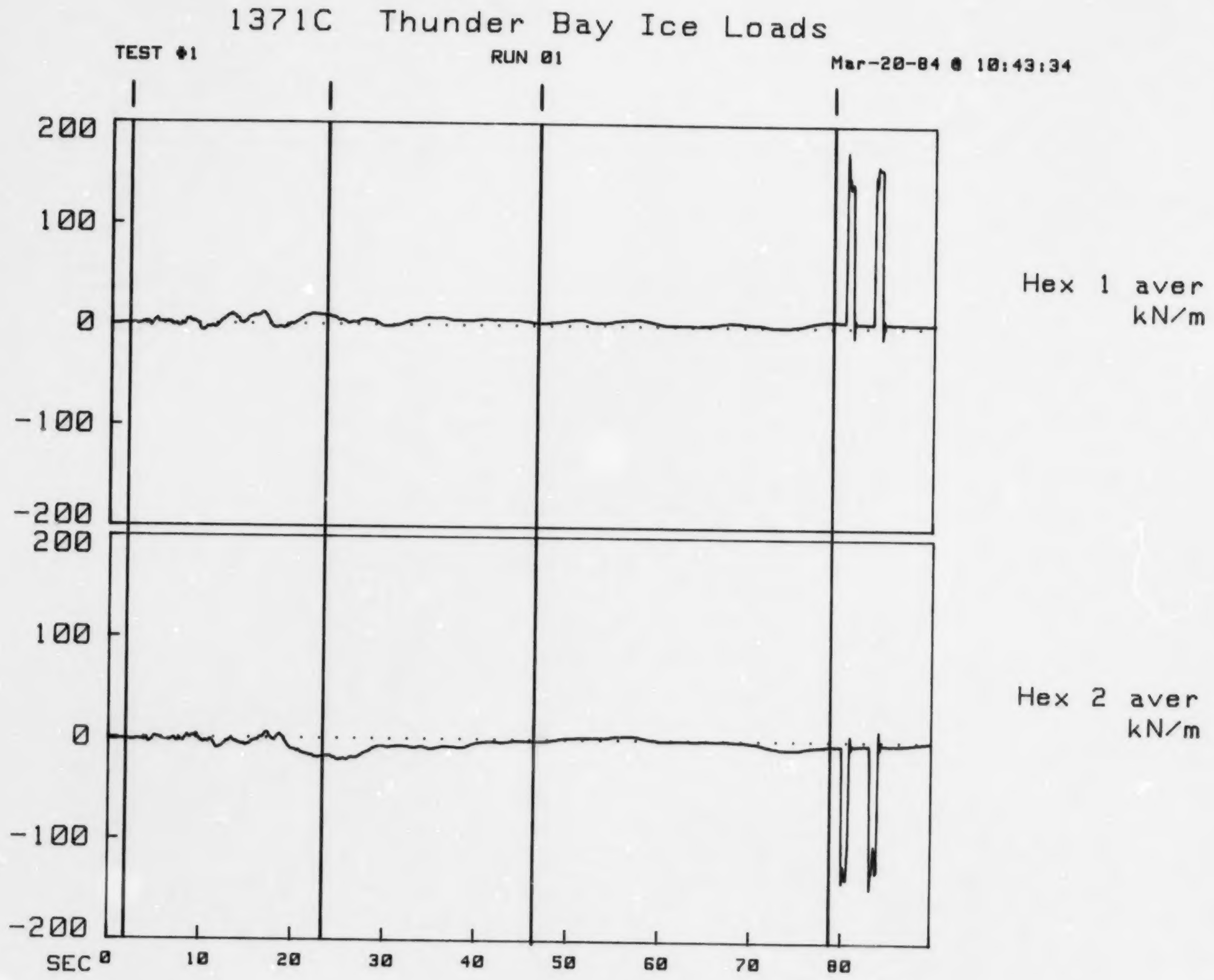


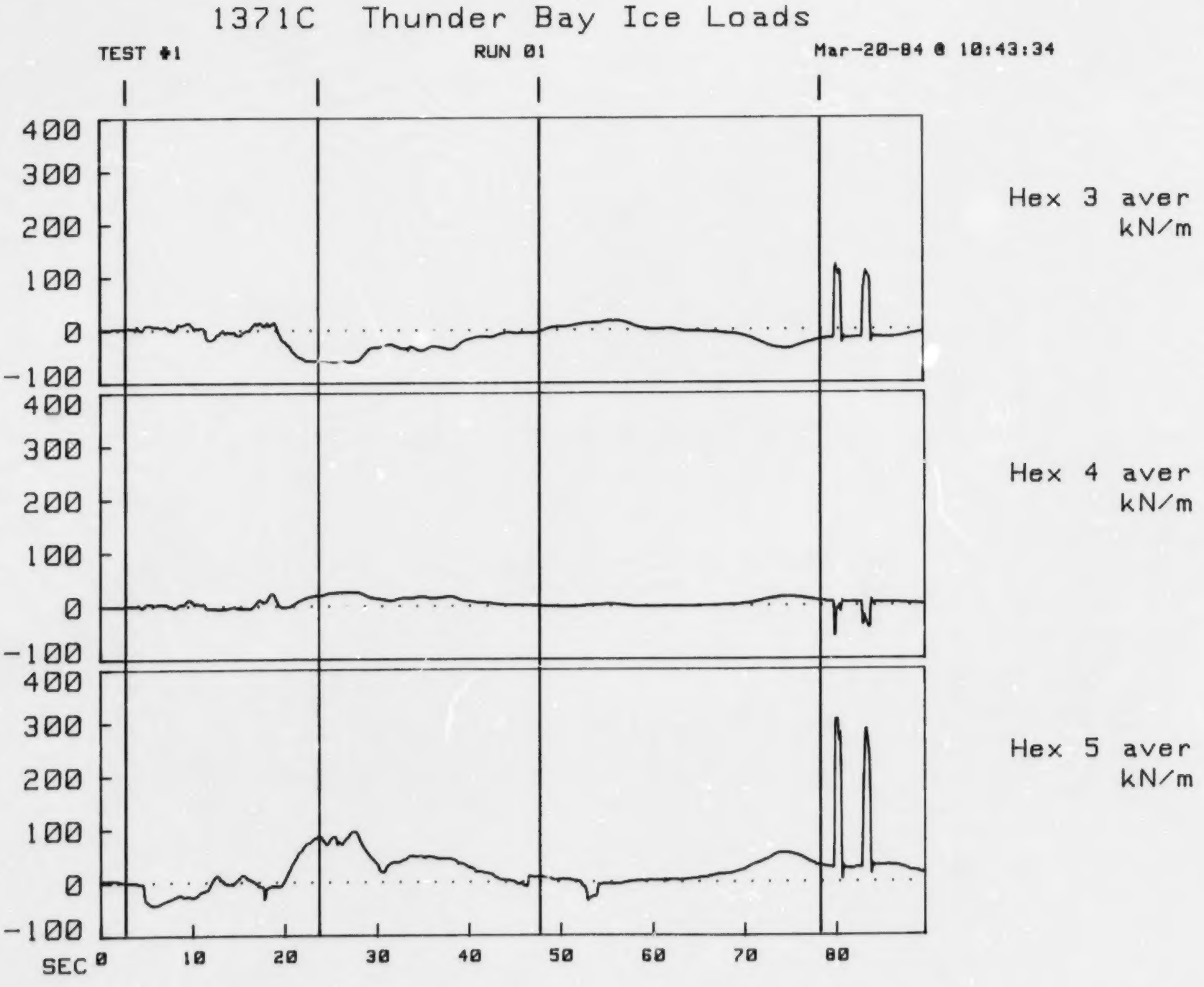
1371C Thunder Bay Ice Loads

TEST #1 RUN 01 Mar-20-84 @ 10:43:34




1371C Thunder Bay Ice Loads
TEST #1
RUN 01
Mar-20-84 @ 10:43:34
|< 1st >|< 2nd >|< 3rd >|
Hexpack 4
kPa
Hexpack 5
kPa
Accel
g'S
20
10
0
-10
-20
-30
250
200
150
100
50
0
-50
.10
0.00
-.10
SEC 0
10
20
30
40
50
60
70
80


1371C Thunder Bay Ice Loads
TEST #1
RUN 01
Mar-20-84 @ 10:43:34
Hex 1 aver
kN/m
Hex 2 aver
kN/m
200
100
0
-100
-200
200
100
0
-100
-200
SEC
0
10
20
30
40
50
60
70
80


1371C Thunder Bay Ice Loads
TEST #1
RUN 01
Mar-20-84 @ 10:43:34
400
300
200
100
0
-100
Hex 3 aver kN/m
Hex 4 aver kN/m
Hex 5 aver kN/m
SEC
0
10
20
30
40
50
60
70
80

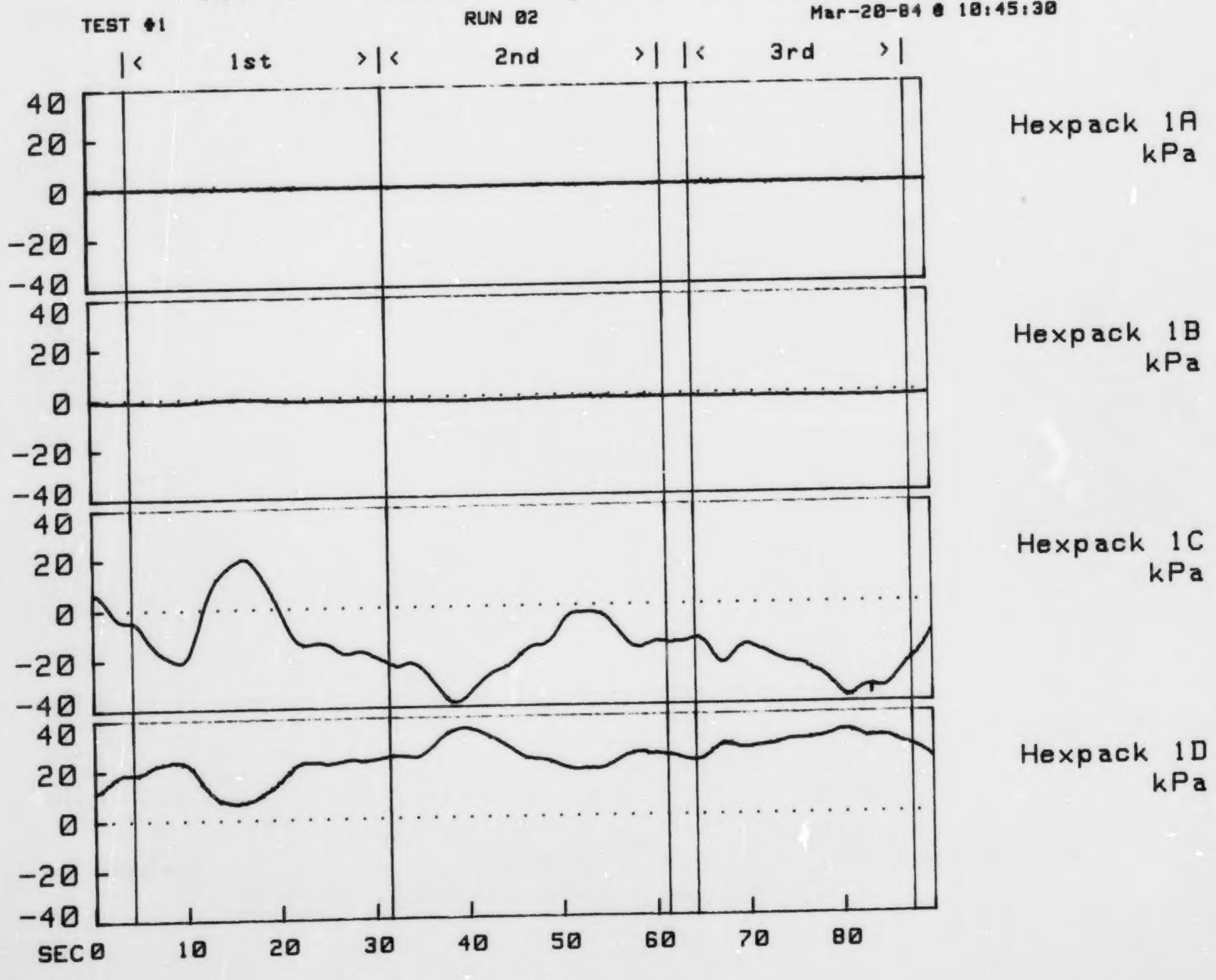
THUNDER BAY ICE LOAD TEST SUMMARY

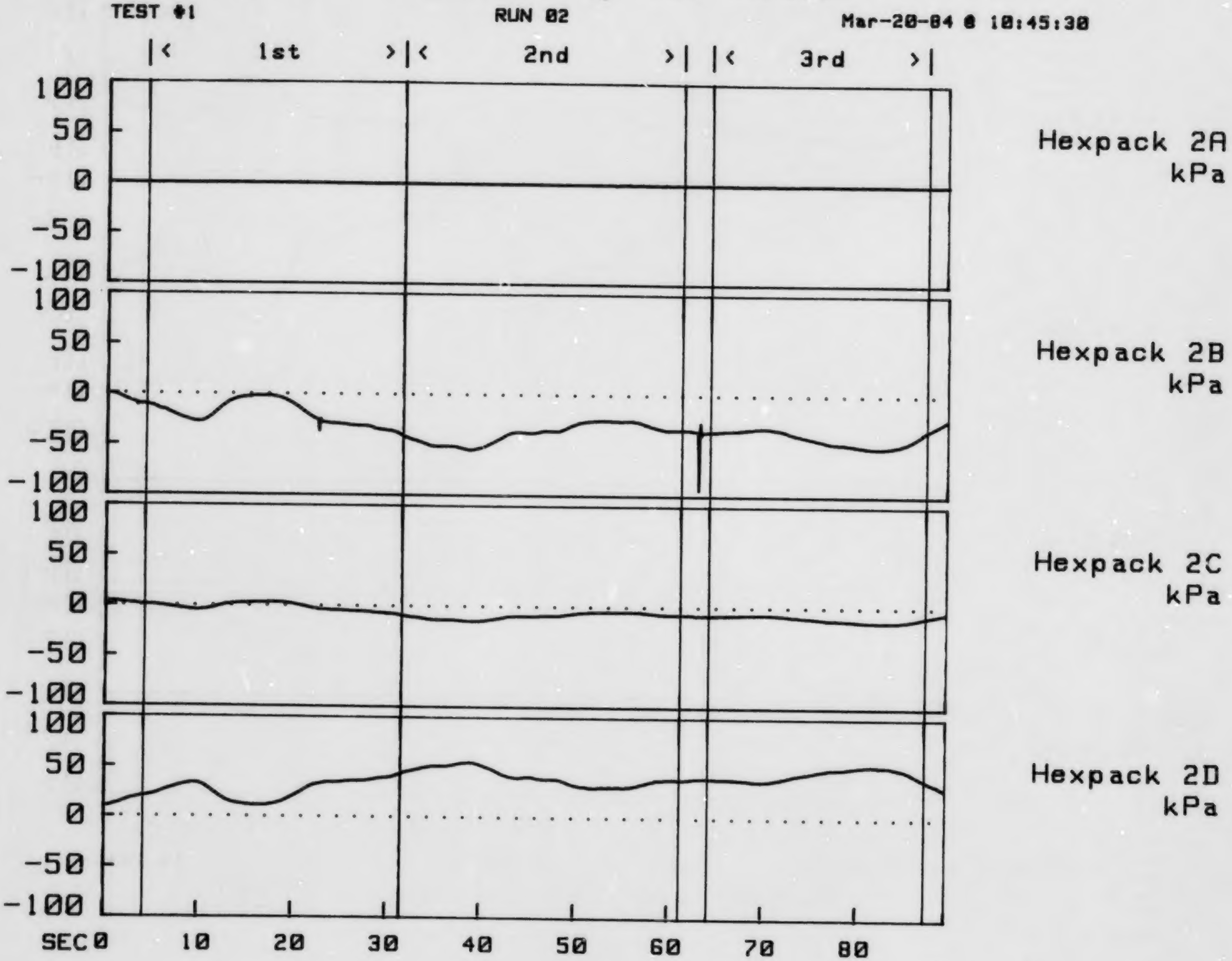
Test #:	1
Run #:	02
Date:	Mar-20-84
Scan Begins at:	10:45:30
Duration of Scan:	90 sec
Scan ends at:	10:47:00
Type of test:	Alexander Henry
Location of Ship:	Ship beyond range of video.

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.45	-0.78	kPa
Hex 1B	0.08	-2.34	kPa
Hex 1C	20.19	-38.62	kPa
Hex 1D	35.85	6.10	kPa
Hex 2A	0.83	-1.12	kPa
Hex 2B	-1.22	-55.25	kPa
Hex 2C	4.02	-14.87	kPa
Hex 2D	55.56	36.98	kPa
Hex 3A	0.48	0.06	kPa
Hex 3B	-1.23	-129.80	kPa
Hex 3C	29.82	17.83	kPa
Hex 3D	78.36	28.67	kPa
Hex 4	3.10	0.37	kPa
Hex 5	15.73	-2.92	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	7.92	1.82	kN/m
Hex 2 aver	4.87	-3.72	kN/m
Hex 3 aver	15.06	-20.76	kN/m
Hex 4 aver	6.20	0.73	kN/m
Hex 5 aver	23.60	-4.38	kN/m

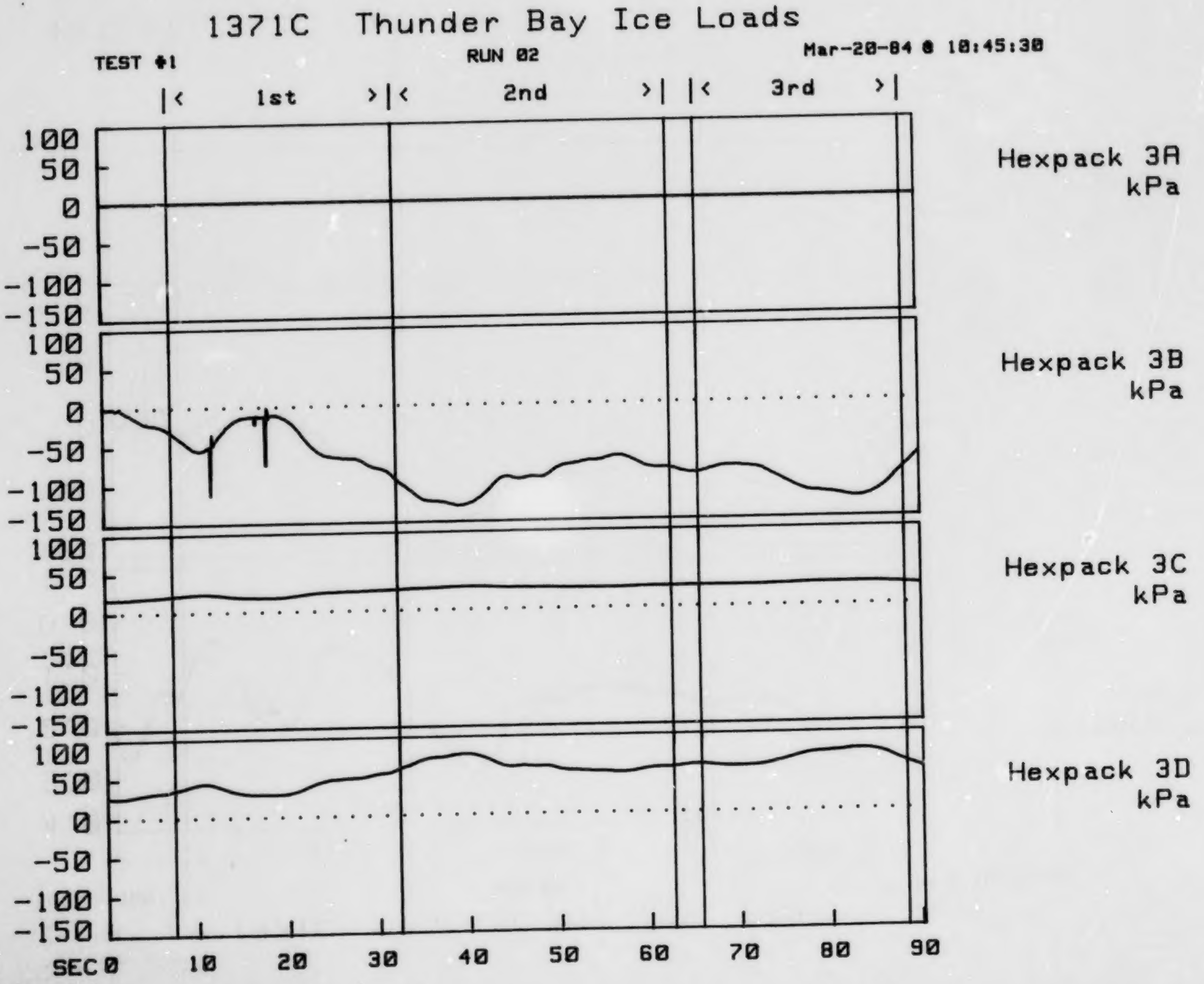
Comments:

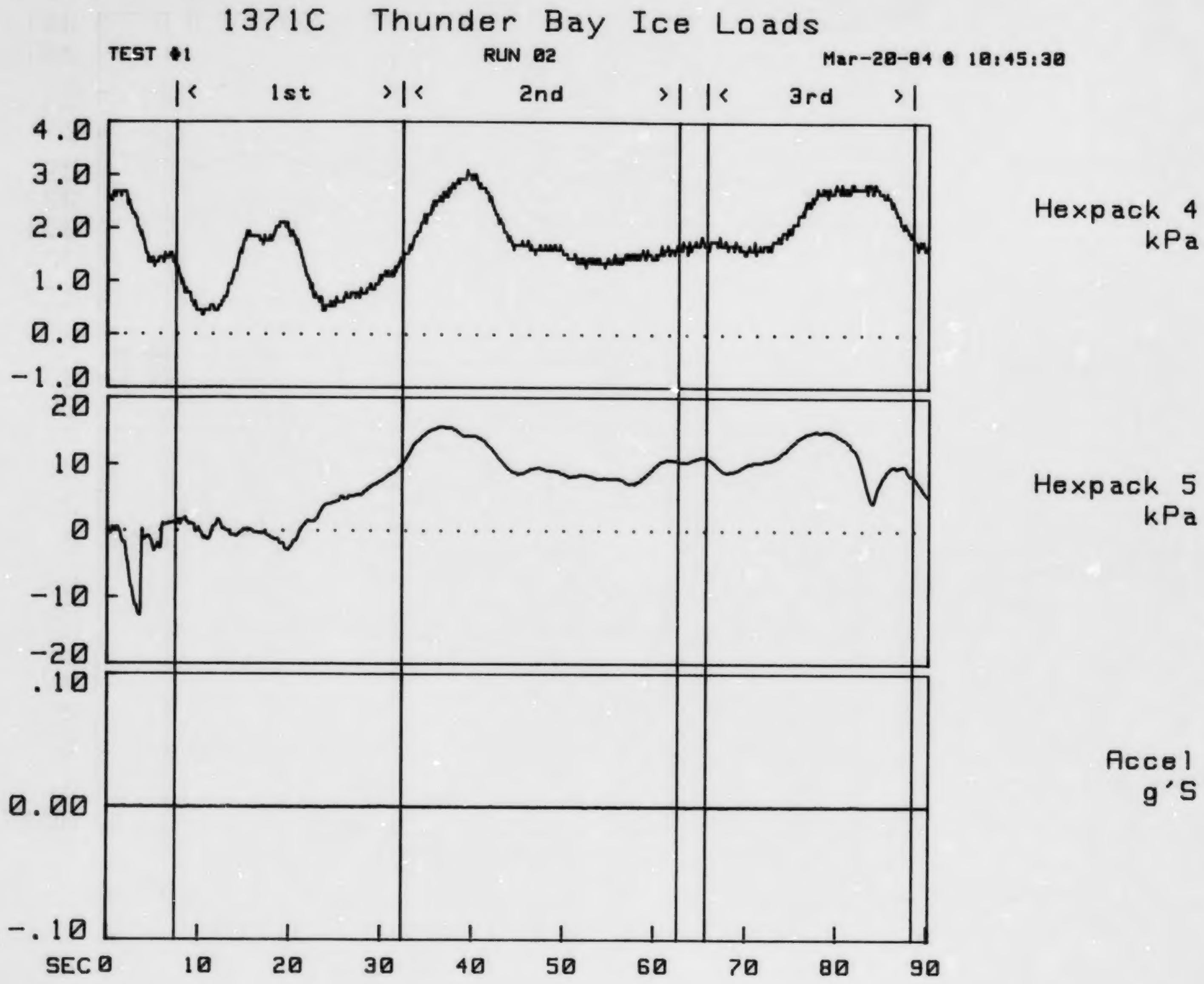
1371C Thunder Bay Ice Loads

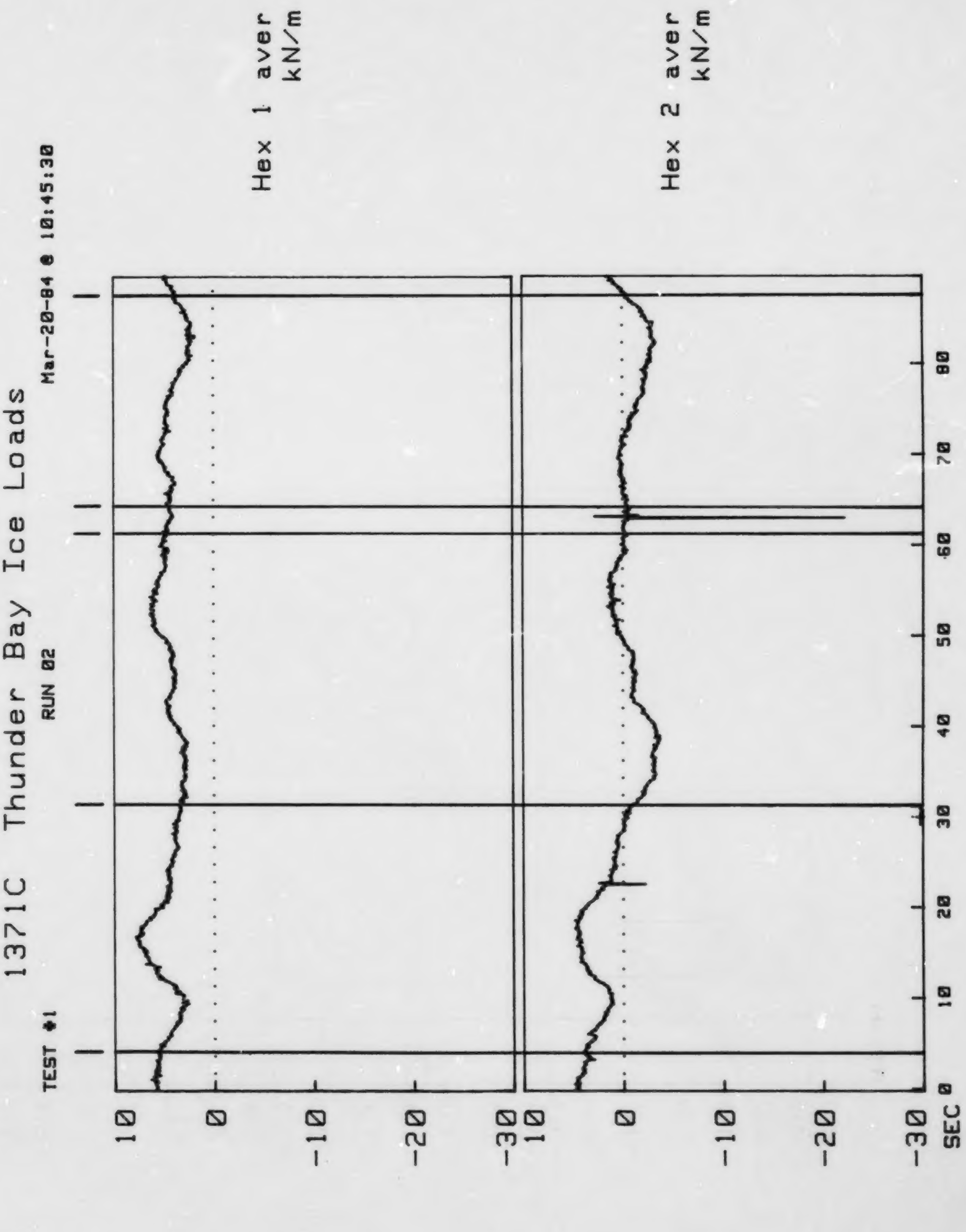


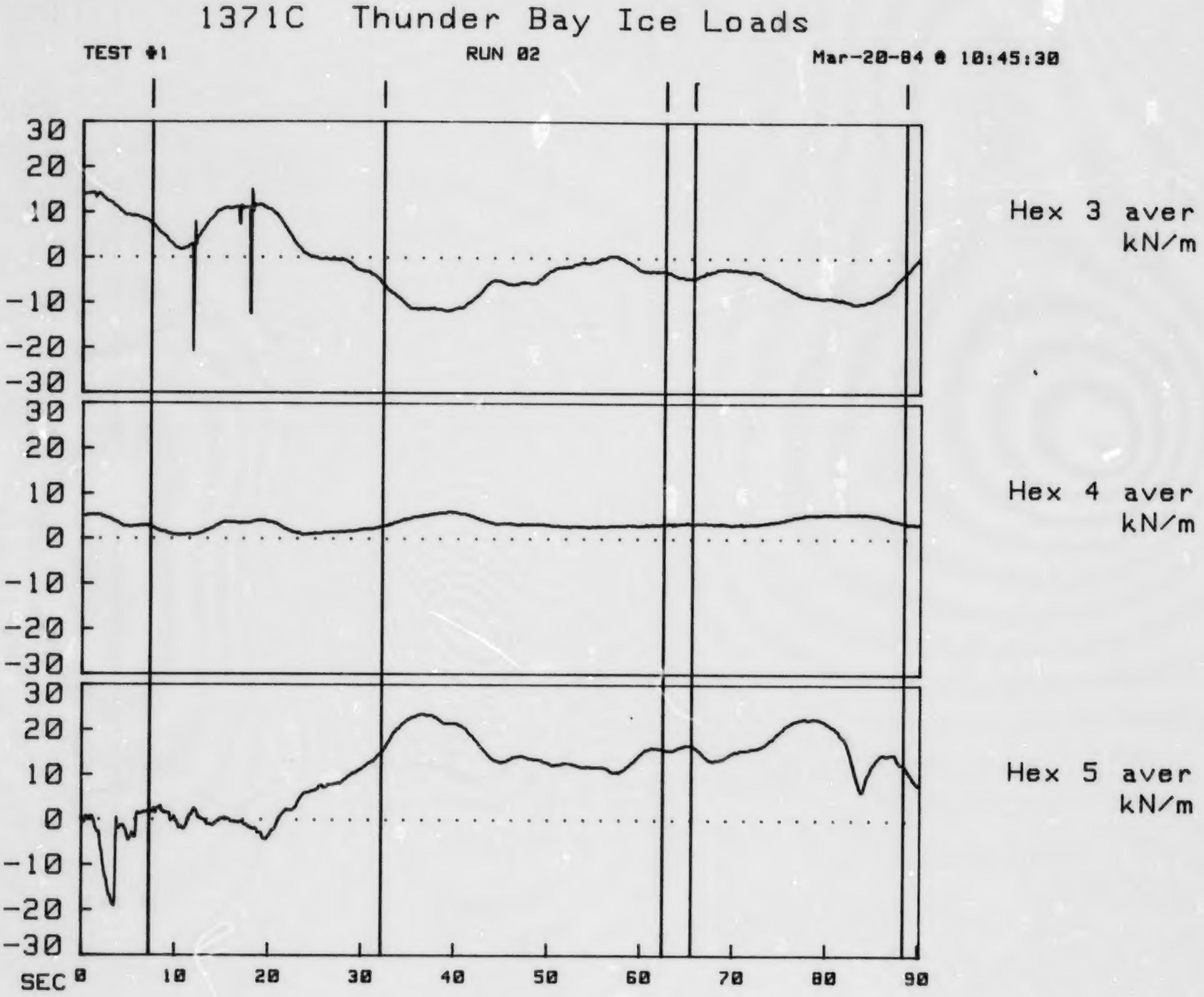


1371C Thunder Bay Ice Loads


1371C Thunder Bay Ice Loads
TEST #1
RUN 02
Mar-20-84 @ 10:45:30
|< 1st >|< 2nd >| |< 3rd >|
100
50
0
-50
-100
-150
Hexpack 3A
kPa
Hexpack 3B
kPa
Hexpack 3C
kPa
Hexpack 3D
kPa
SEC 0
10
20
30
40
50
60
70
80
90


1371C Thunder Bay Ice Loads
TEST #1
RUN 02
Mar-20-84 @ 10:45:30
|< 1st >|< 2nd >| |< 3rd >|
4.0
3.0
2.0
1.0
0.0
-1.0
Hexpack 4
kPa
20
10
0
-10
-20
Hexpack 5
kPa
.10
0.00
-.10
Accel
g'S
SEC 0
10
20
30
40
50
60
70
80
90


1371C Thunder Bay Ice Loads
RUN 02
TEST #1
Mar-20-84 @ 10:45:30
Hex 1 aver
kN/m
Hex 2 aver
kN/m
10
0
-10
-20
-30
10
0
-10
-20
-30
SEC
0
10
20
30
40
50
60
70
80


1371C Thunder Bay Ice Loads
TEST #1
RUN 02
Mar-20-84 @ 10:45:30
30
20
10
0
-10
-20
-30
Hex 3 aver
kN/m
Hex 4 aver
kN/m
Hex 5 aver
kN/m
SEC
0
10
20
30
40
50
60
70
80
90

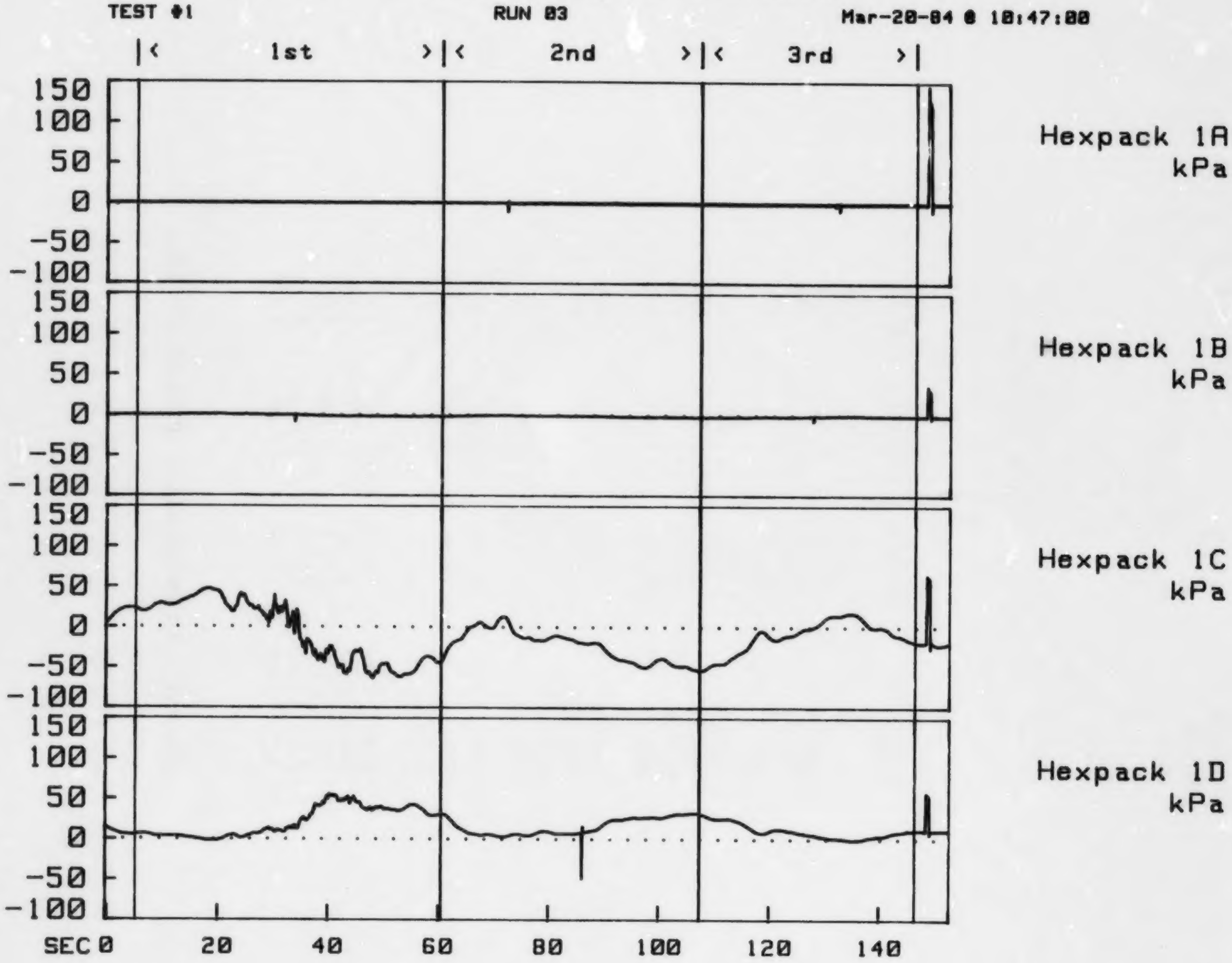
THUNDER BAY ICE LOAD TEST SUMMARY

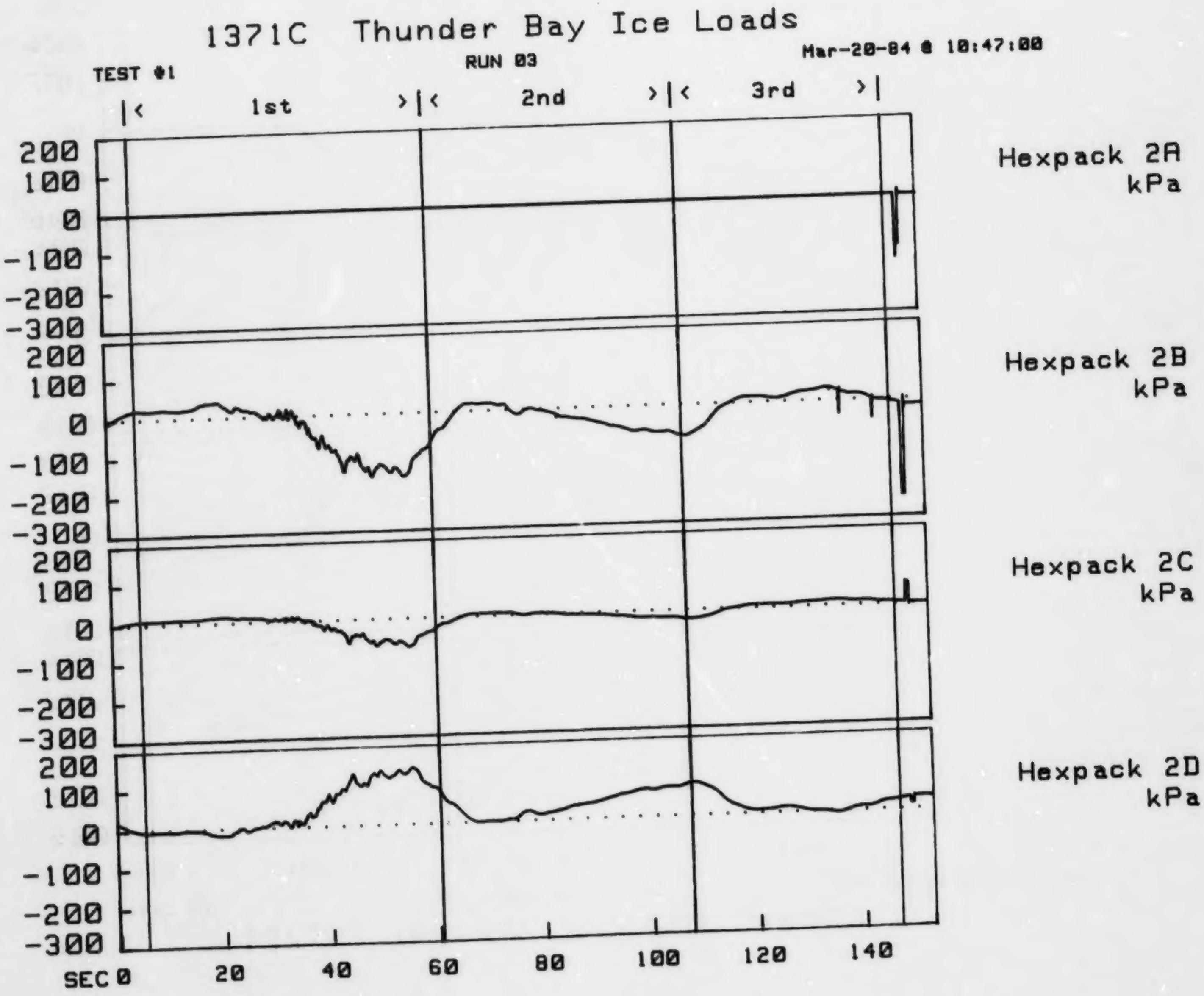
Test #: 1
Run #: 03
Date: Mar-20-84
Scan Begins at: 10:47:00
Duration of Scan: 150 sec
Scan ends at: 10:49:30
Type of test: Alexander Henry
Location of Ship: 120 m E-S-E of dock
Ramming unbroken ice

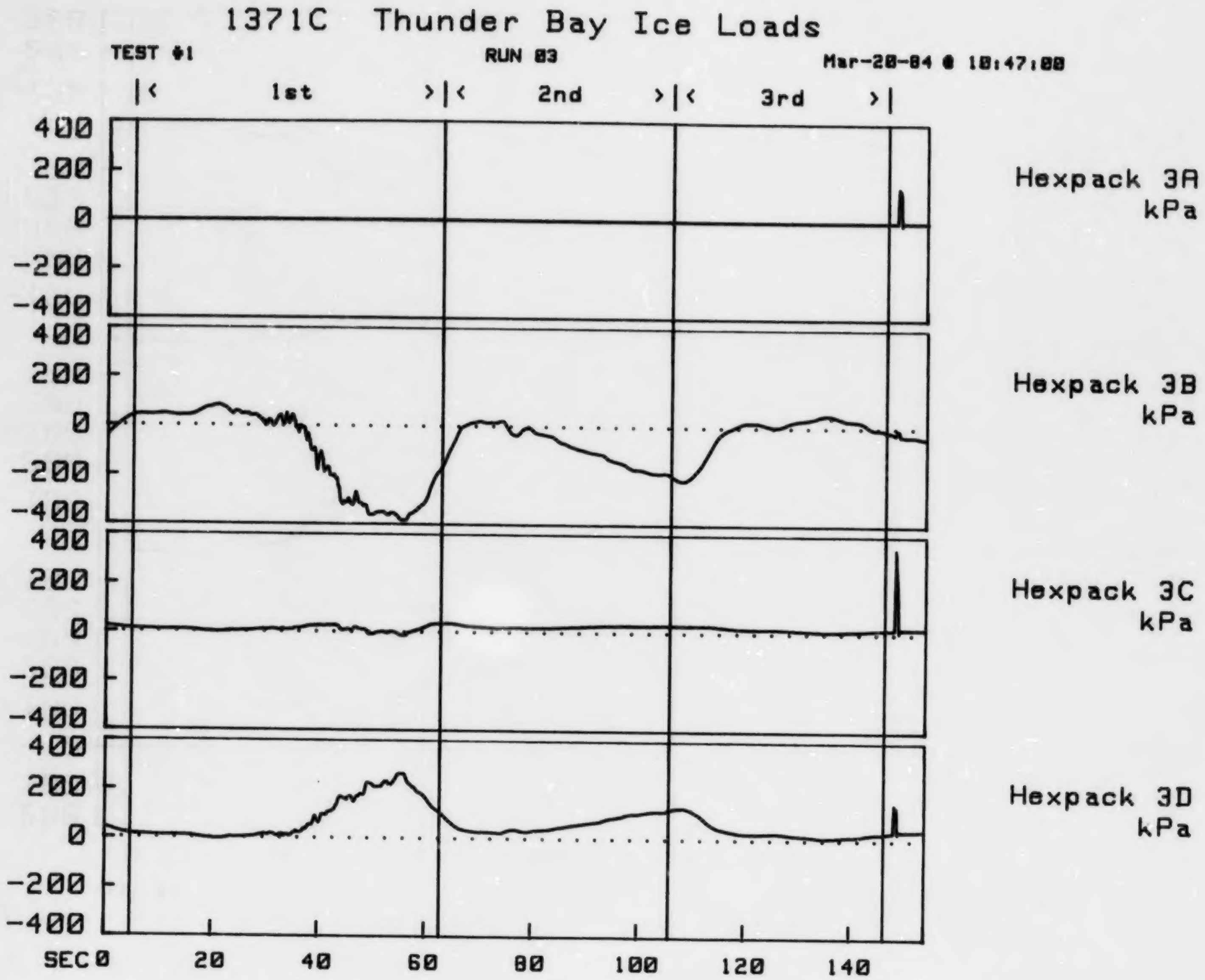
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	0.77	-0.49	kPa
Hex 1B	0.34	-2.51	kPa
Hex 1C	47.87	-64.18	kPa
Hex 1D	56.22	-2.09	kPa
Hex 2A	0.62	-1.02	kPa
Hex 2B	40.95	-161.57	kPa
Hex 2C	16.73	-72.80	kPa
Hex 2D	146.04	-17.92	kPa
Hex 3A	1.52	-0.26	kPa
Hex 3B	85.60	-384.57	kPa
Hex 3C	39.21	-13.63	kPa
Hex 3D	267.49	-5.04	kPa
Hex 4	21.07	0.86	kPa
Hex 5	84.44	-23.24	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	14.82	-3.36	kN/m
Hex 2 aver	17.16	-24.79	kN/m
Hex 3 aver	30.54	-54.08	kN/m
Hex 4 aver	42.13	1.73	kN/m
Hex 5 aver	126.66	-34.86	kN/m

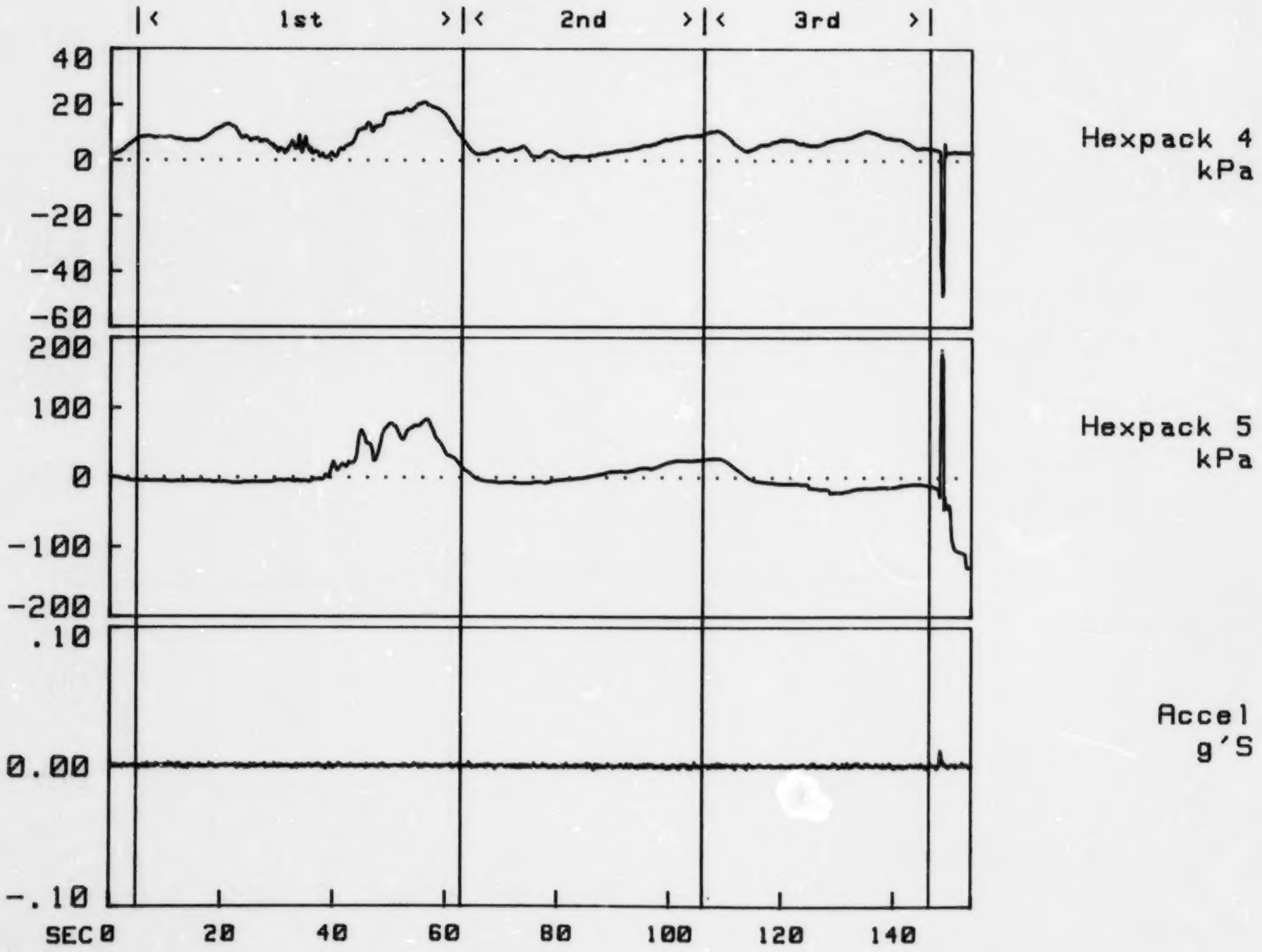
Comments: A communication spike at 148 sec.

1371C Thunder Bay Ice Loads




1371C Thunder Bay Ice Loads
RUN 03
Mar-20-84 @ 10:47:00
TEST #1
|< 1st >|< 2nd >|< 3rd >|
Hexpack 2A kPa
Hexpack 2B kPa
Hexpack 2C kPa
Hexpack 2D kPa
200
100
0
-100
-200
-300
SEC 0
20
40
60
80
100
120
140

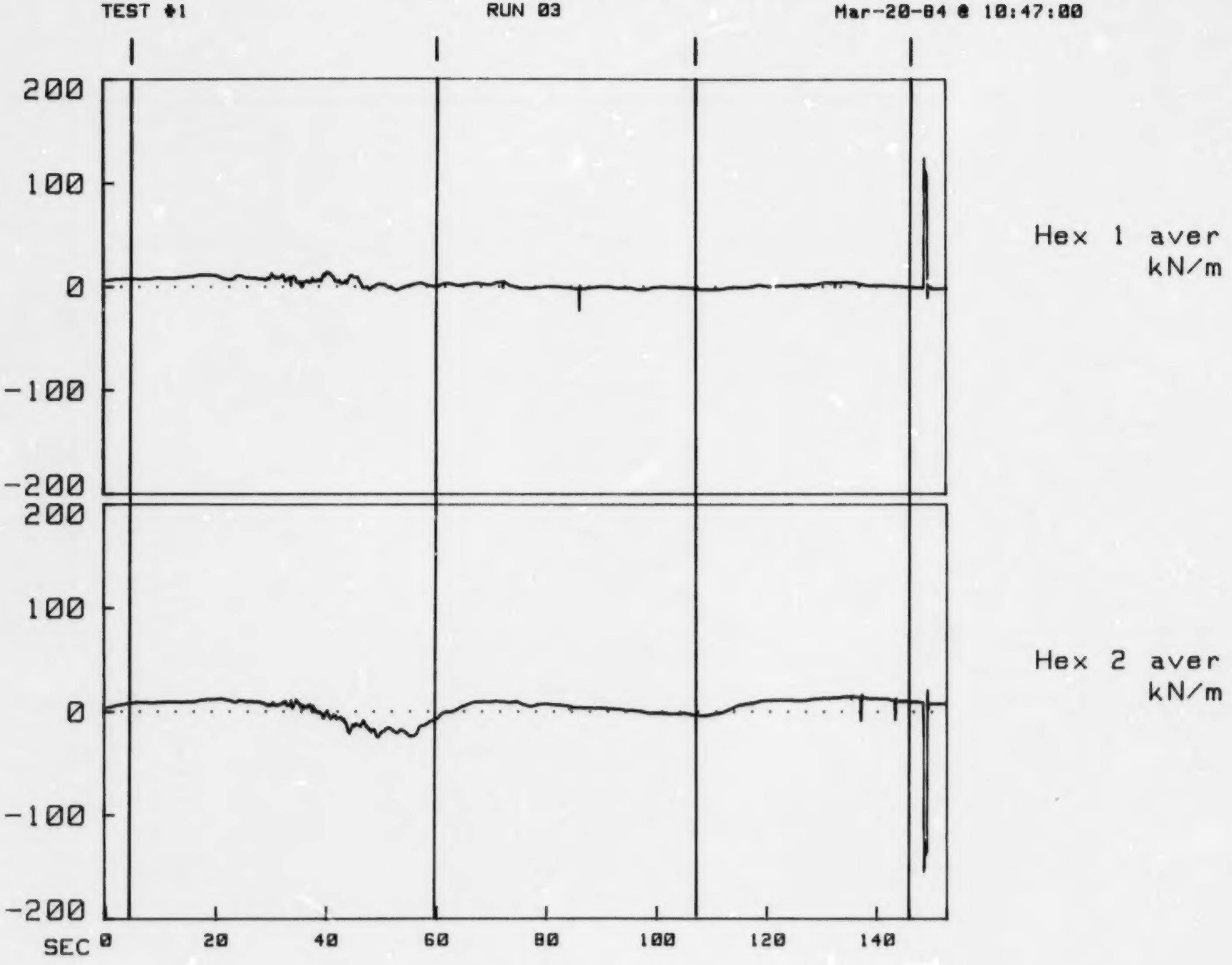

1371C Thunder Bay Ice Loads
TEST #1
RUN 03
Mar-28-84 @ 10:47:00
|< 1st >|< 2nd >|< 3rd >|
400
200
0
-200
-400
Hexpack 3A
kPa
Hexpack 3B
kPa
Hexpack 3C
kPa
Hexpack 3D
kPa
SEC
0
20
40
60
80
100
120
140



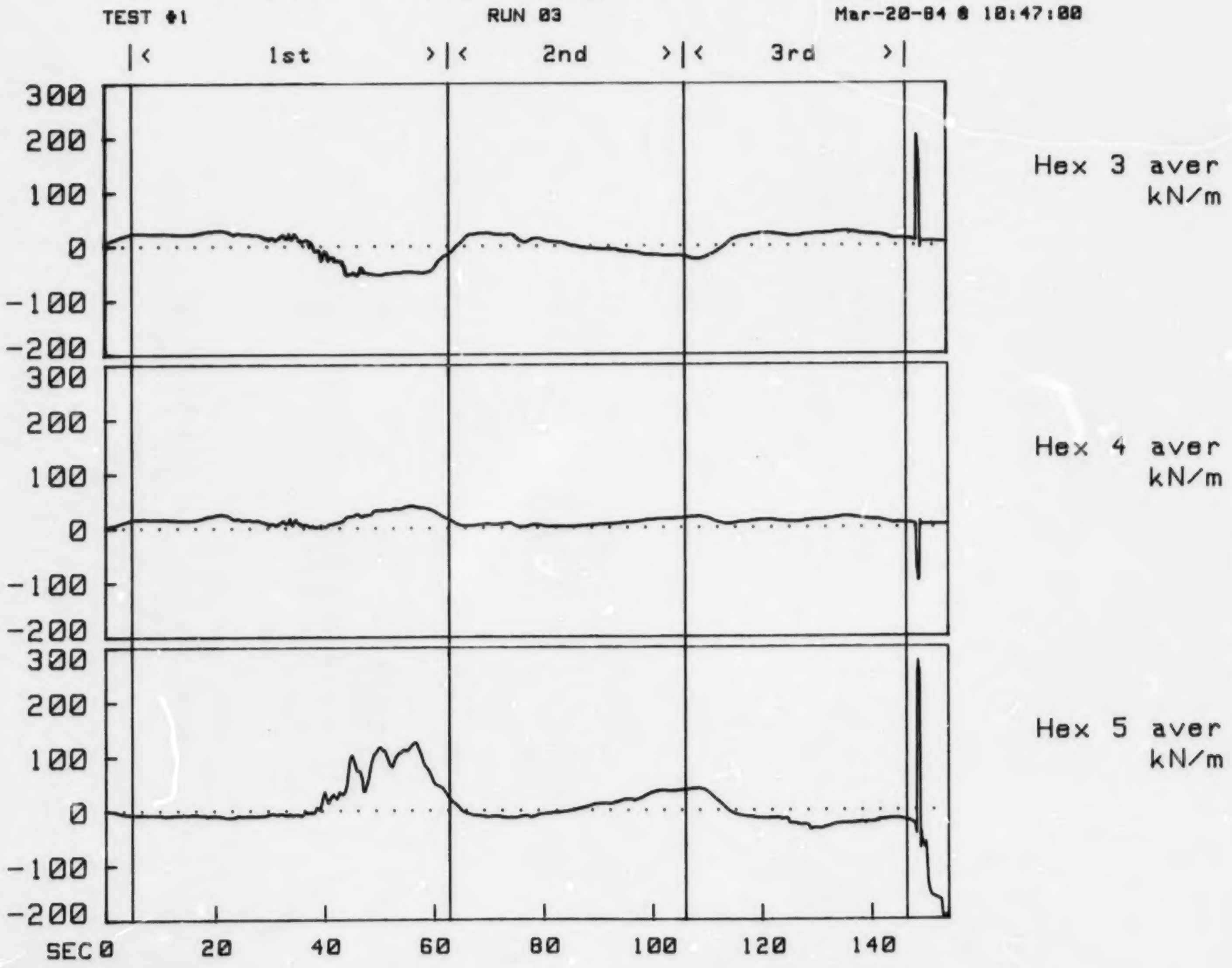
1371C Thunder Bay Ice Loads

TEST #1 RUN 03 Mar-20-84 @ 10:47:00

1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads



THUNDER BAY ICE LOAD TEST SUMMARY

Test #: 1
Run #: 04
Date: Mar-20-84
Scan Begins at: 10:49:54
Duration of Scan: 150 sec
Scan ends at: 10:52:24
Type of test: Alexander Henry
Location of Ship: 80 m E-S-E of dock
Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.45	-2.04	kPa
Hex 1B	0.69	-2.86	kPa
Hex 1C	29.61	-72.44	kPa
Hex 1D	54.06	1.04	kPa
Hex 2A	1.85	-2.97	kPa
Hex 2B	3.27	-144.30	kPa
Hex 2C	6.50	-57.86	kPa
Hex 2D	148.74	15.70	kPa
Hex 3A	5.08	-0.57	kPa
Hex 3B	-6.74	-360.15	kPa
Hex 3C	42.68	0.80	kPa
Hex 3D	251.95	46.18	kPa
Hex 4	22.23	3.35	kPa
Hex 5	45.55	-76.56	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	8.54	-6.57	kN/m
Hex 2 aver	9.05	-17.32	kN/m
Hex 3 aver	23.44	-44.26	kN/m
Hex 4 aver	44.45	6.69	kN/m
Hex 5 aver	68.32	-113.90	kN/m

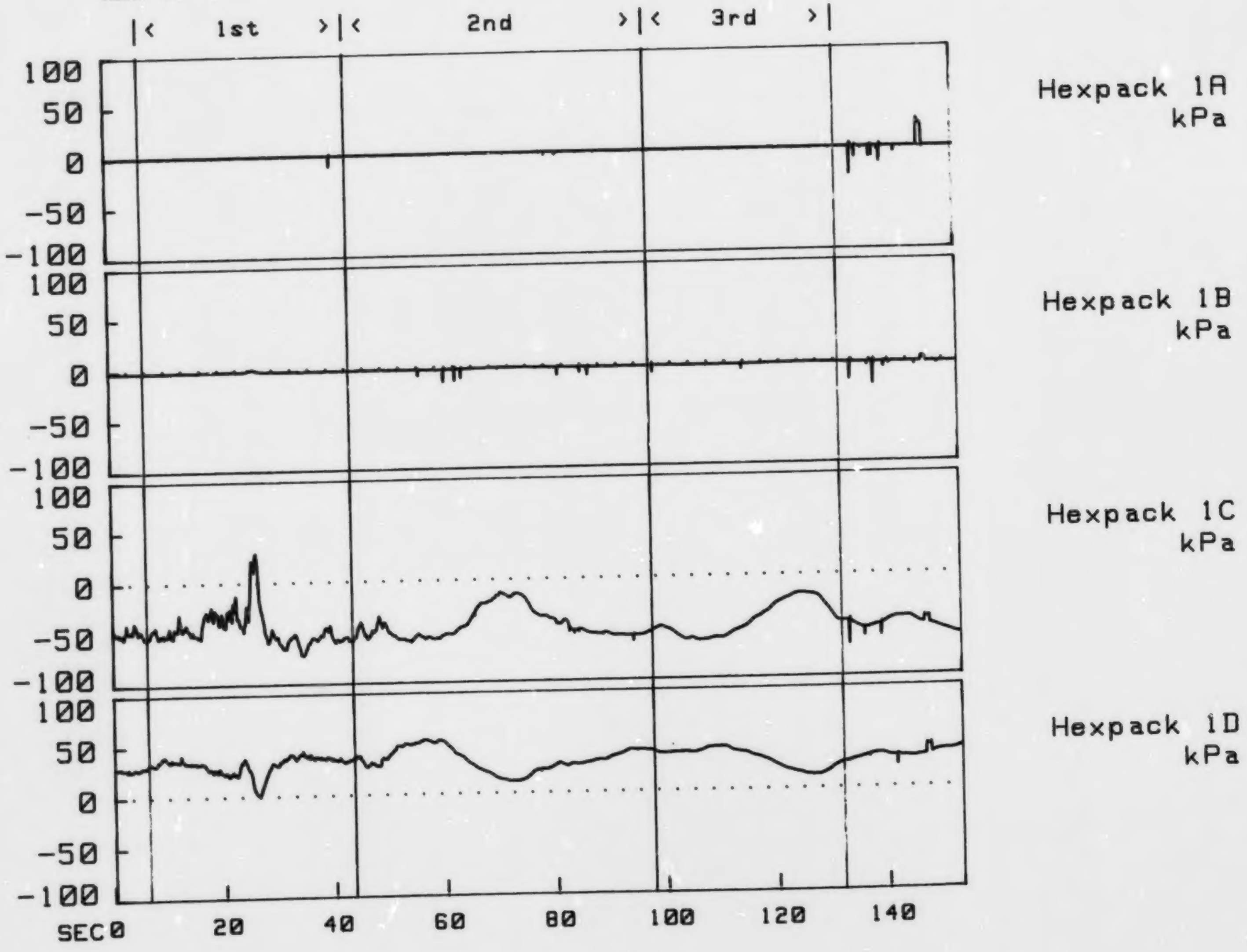
Comments: Hexpack 5 not functioning for first 56 seconds. A communication spike at 145 seconds.

1371C Thunder Bay Ice Loads

TEST #1

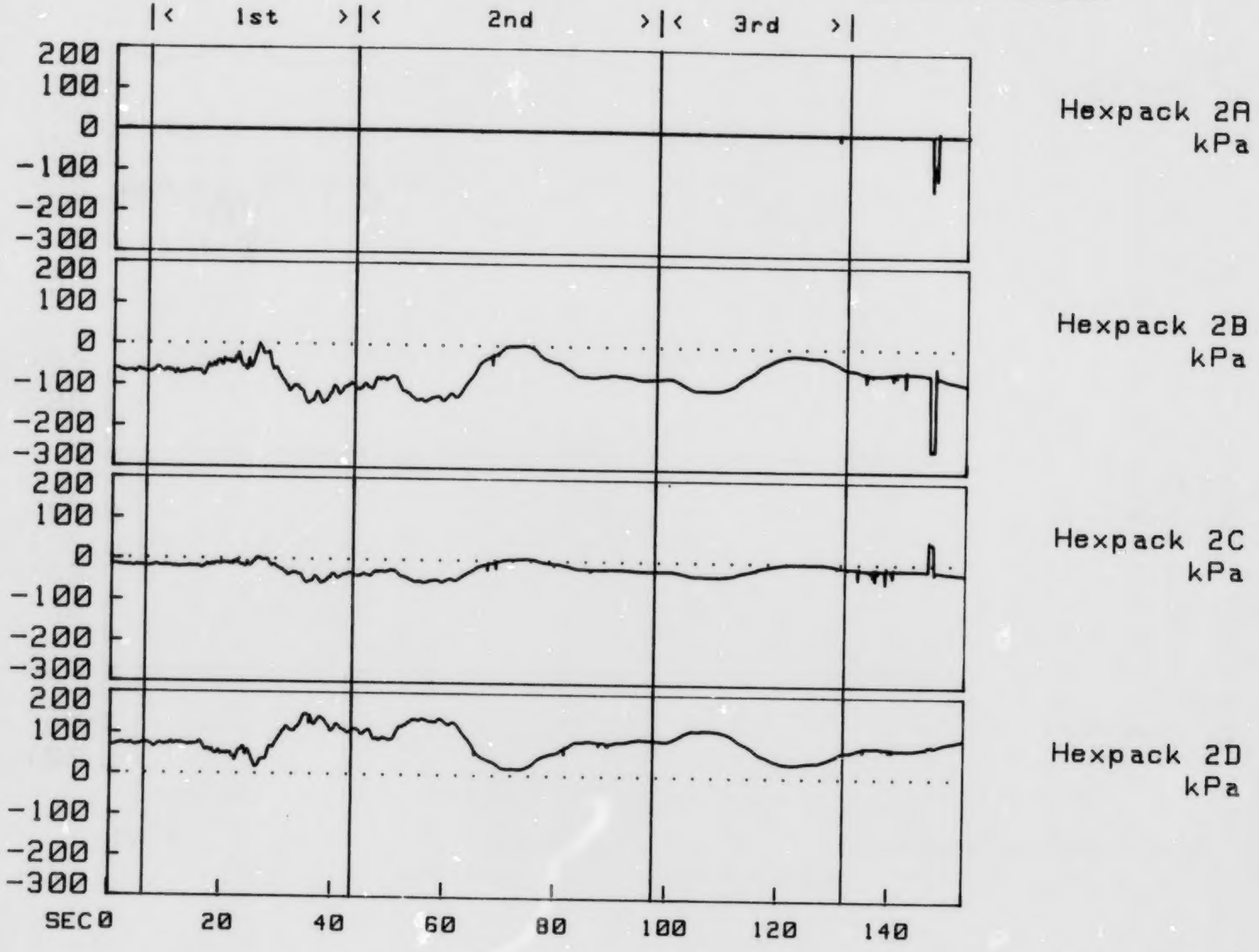
RUN 04

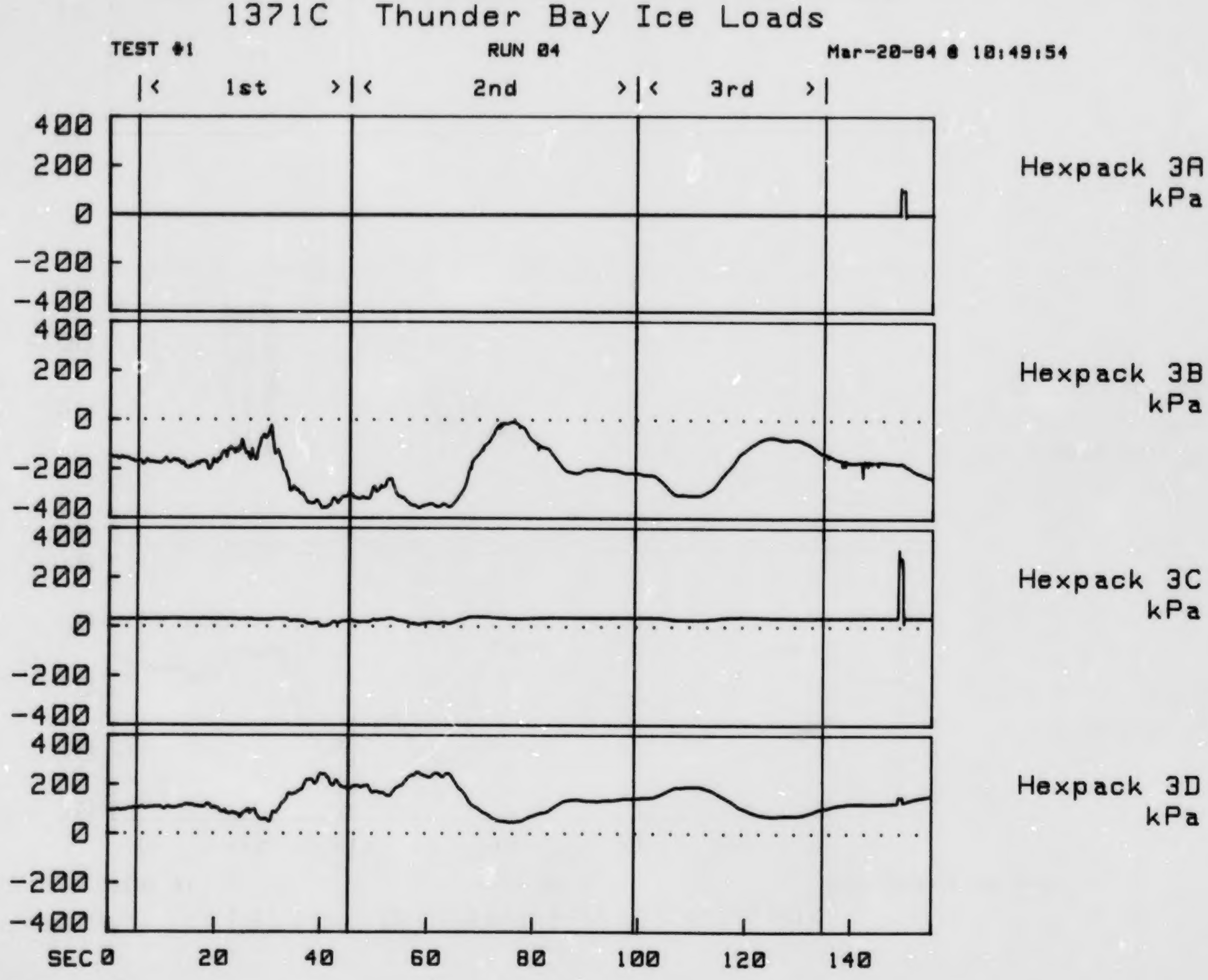
Mar-20-84 @ 10:49:54

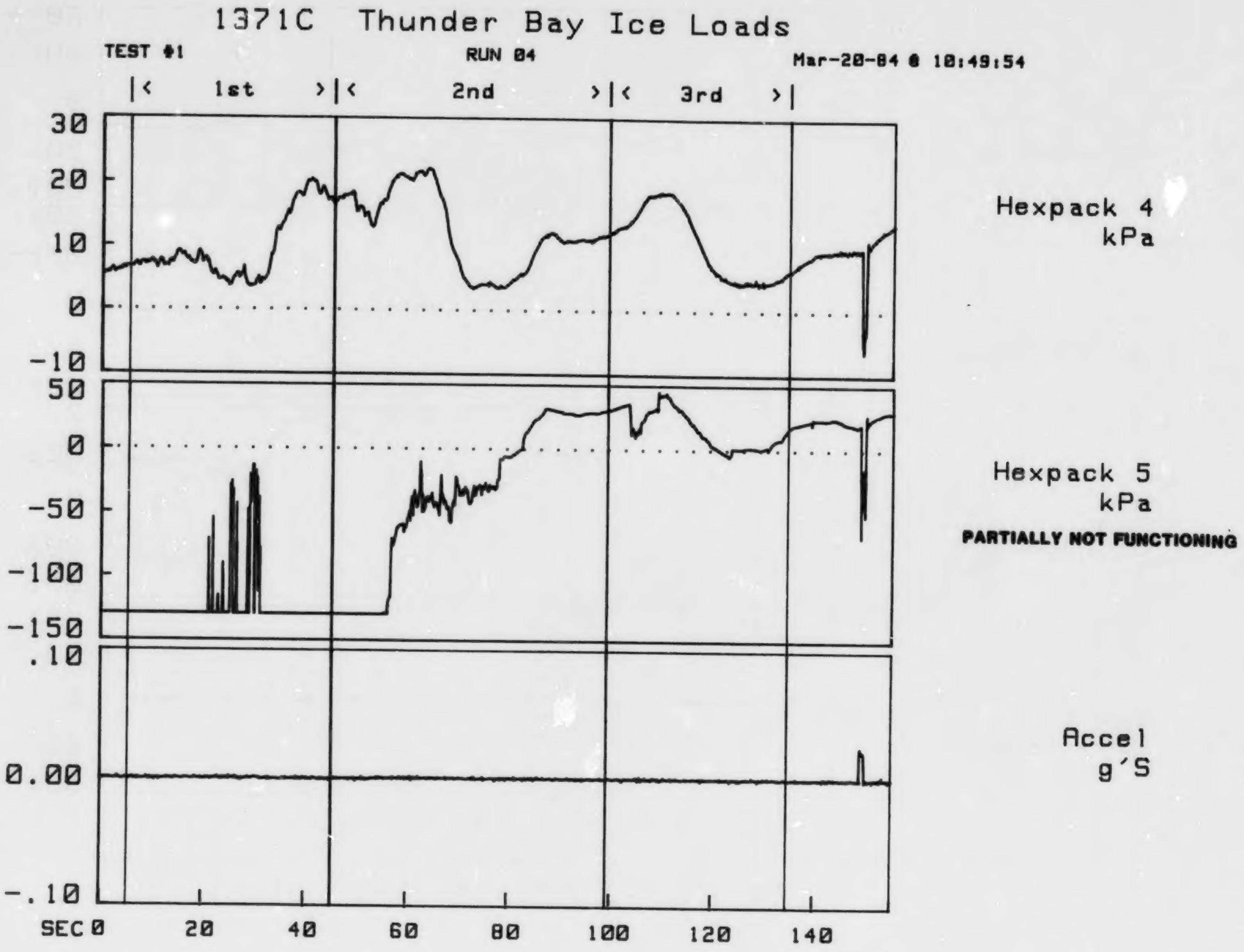


1371C Thunder Bay Ice Loads

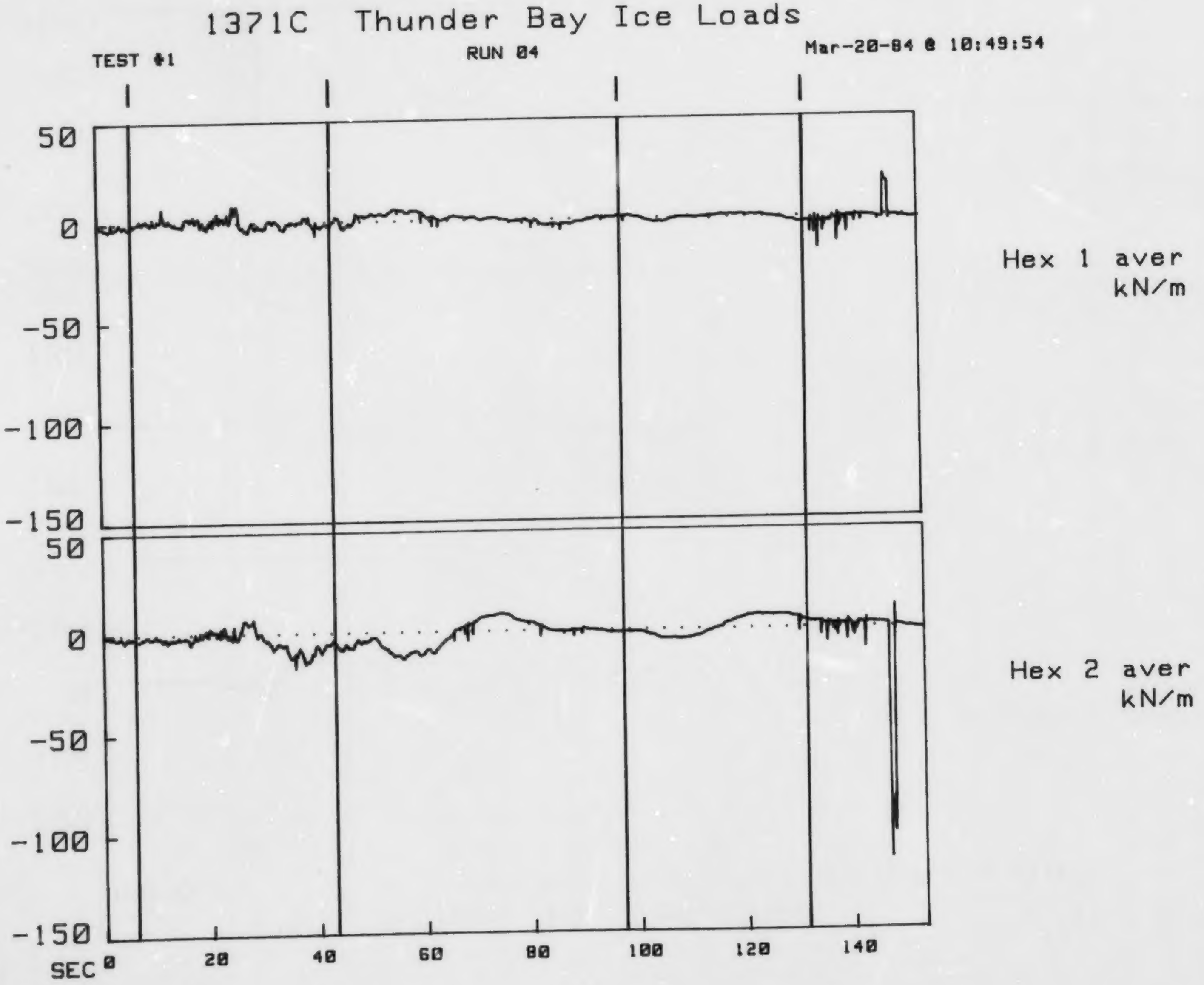
TEST #1 RUN 04 Mar-20-84 @ 10:49:54




1371C Thunder Bay Ice Loads
TEST #1
RUN 04
Mar-20-84 @ 10:49:54
|< 1st >|< 2nd >|< 3rd >|
400
200
0
-200
-400
Hexpack 3A
kPa
Hexpack 3B
kPa
Hexpack 3C
kPa
Hexpack 3D
kPa
SEC 0
20
40
60
80
100
120
140

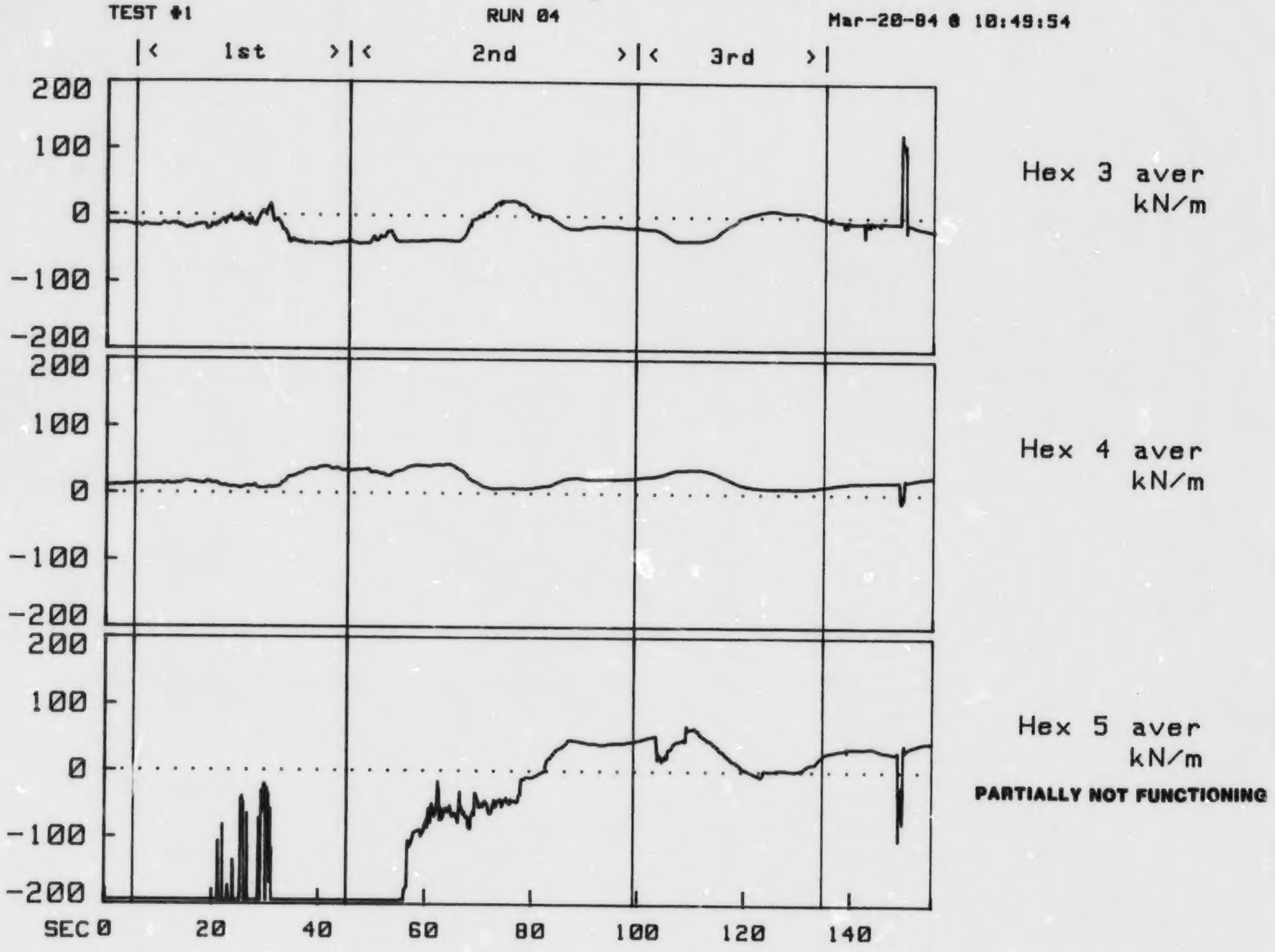


PARTIALLY NOT FUNCTIONING



1371C Thunder Bay Ice Loads

1371C Thunder Bay Ice Loads

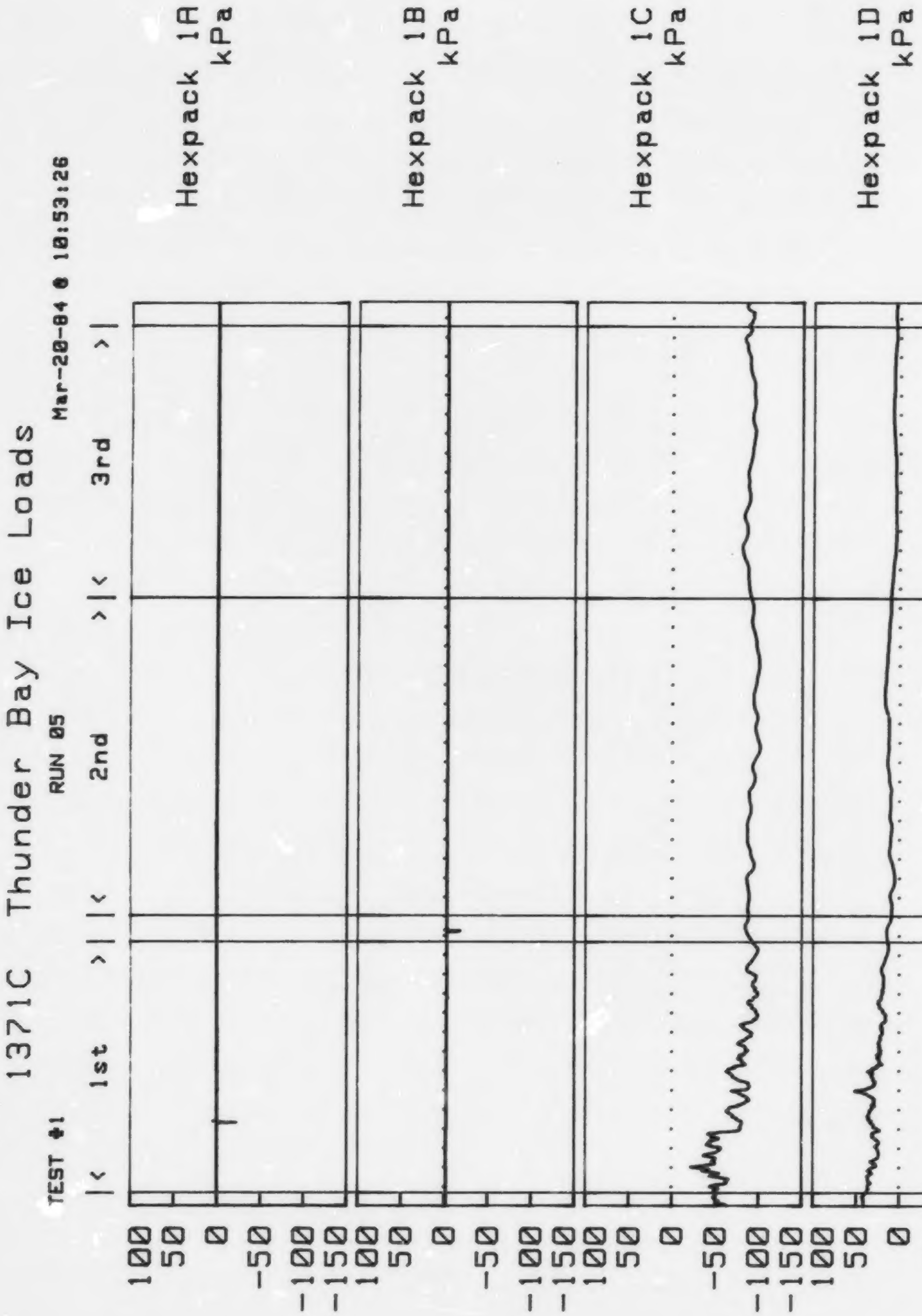


THUNDER BAY ICE LOAD TEST SUMMARY

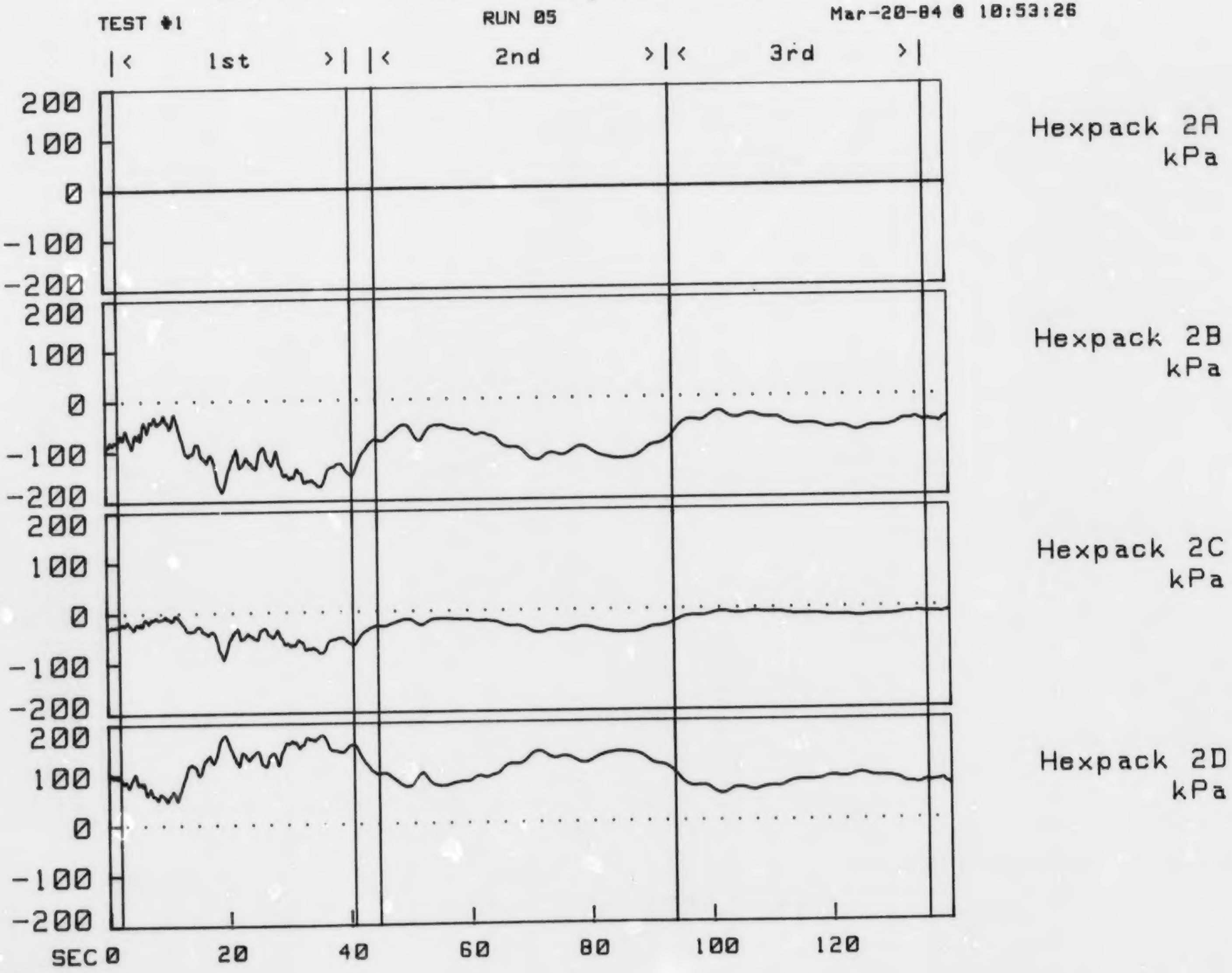
Test #: 1
Run #: 05
Date: Mar-20-84
Scan Begins at: 10:53:26
Duration of Scan: 140 sec
Scan ends at: 10:55:46
Type of test: Alexander Henry
Location of Ship: Starts 60 m E-S-E of dock
Ends 15 m east of dock
Ramming unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.16	-0.10	kPa
Hex 1B	-1.21	-4.41	kPa
Hex 1C	-22.09	-101.75	kPa
Hex 1D	52.23	3.95	kPa
Hex 2A	0.93	-0.71	kPa
Hex 2B	-25.87	-181.40	kPa
Hex 2C	-3.80	-93.33	kPa
Hex 2D	178.06	47.07	kPa
Hex 3A	1.52	-0.05	kPa
Hex 3B	-83.53	-416.46	kPa
Hex 3C	44.07	-29.96	kPa
Hex 3D	355.49	84.27	kPa
Hex 4	28.11	5.58	kPa
Hex 5	79.77	-19.24	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	5.62	-21.79	kN/m
Hex 2 aver	8.22	-24.53	kN/m
Hex 3 aver	11.84	-38.49	kN/m
Hex 4 aver	56.21	11.17	kN/m
Hex 5 aver	119.66	-28.87	kN/m

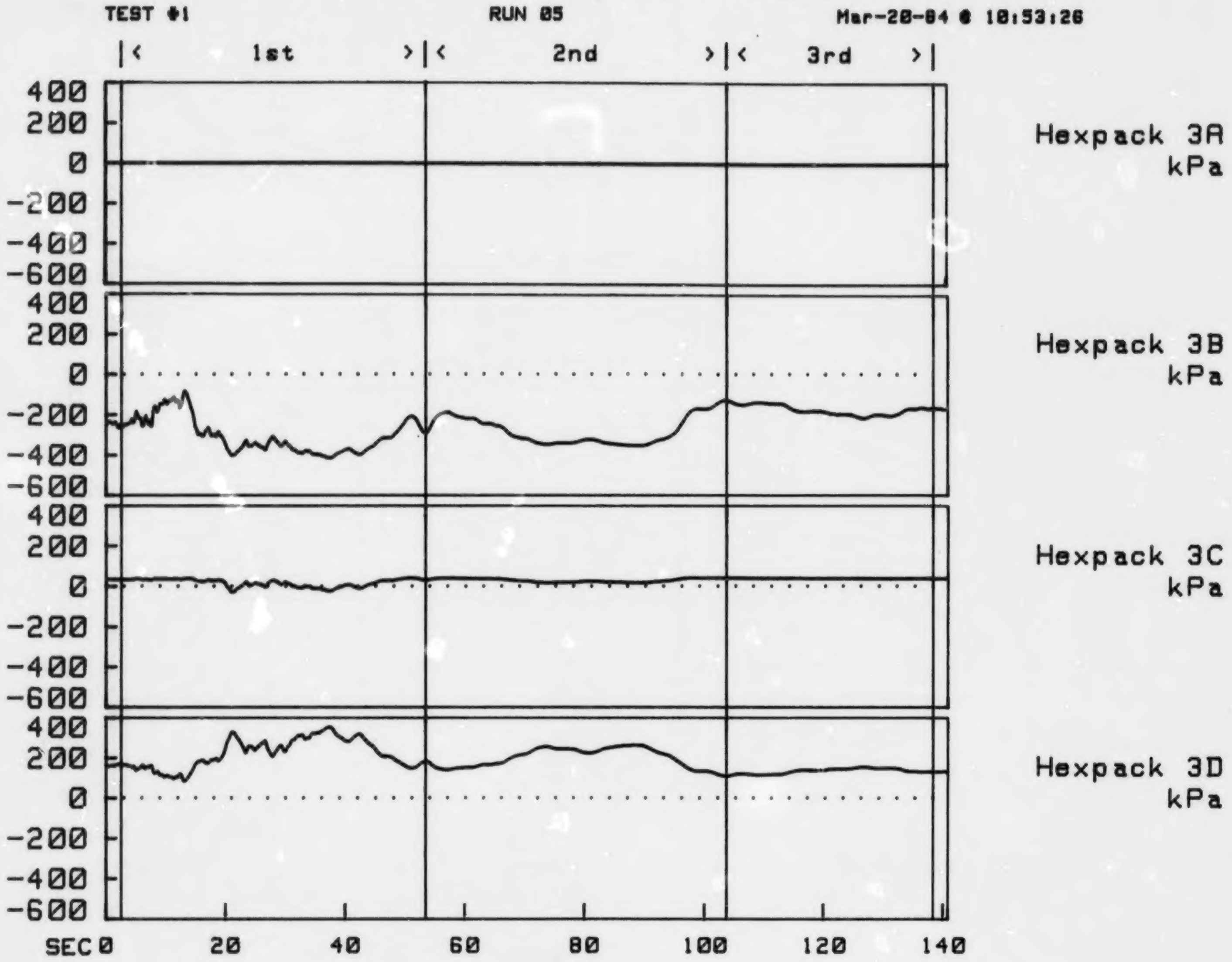
Comments:


1371C Thunder Bay Ice Loads
TEST #1
RUN 05
Mar-20-84 @ 10:53:26
|< 1st >||< 2nd >|< 3rd >|
Hexpack 1A kPa
Hexpack 1B kPa
Hexpack 1C kPa
Hexpack 1D kPa
100
50
0
-50
-100
-150
SEC 0
20
40
60
80
100
120

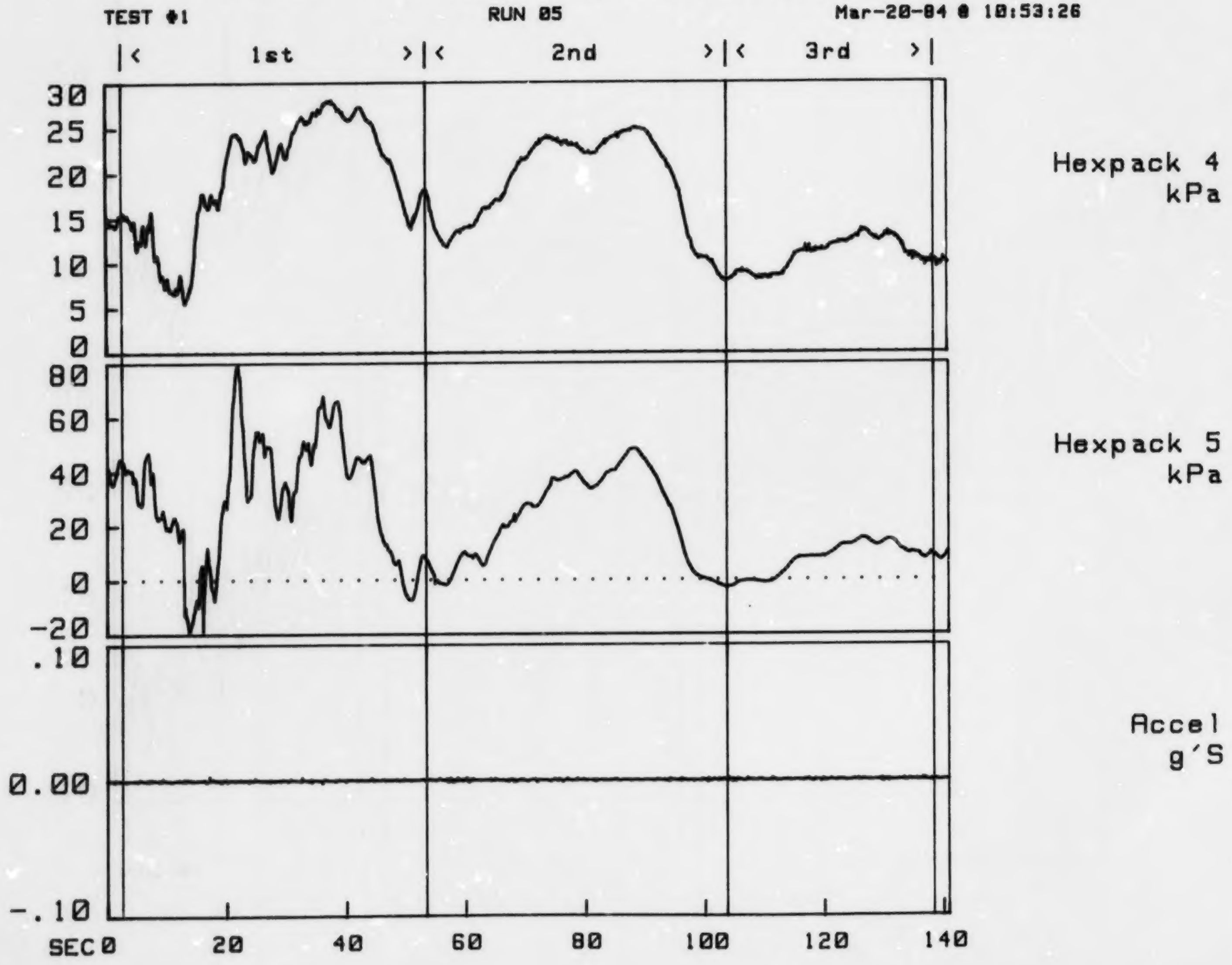
1371C Thunder Bay Ice Loads

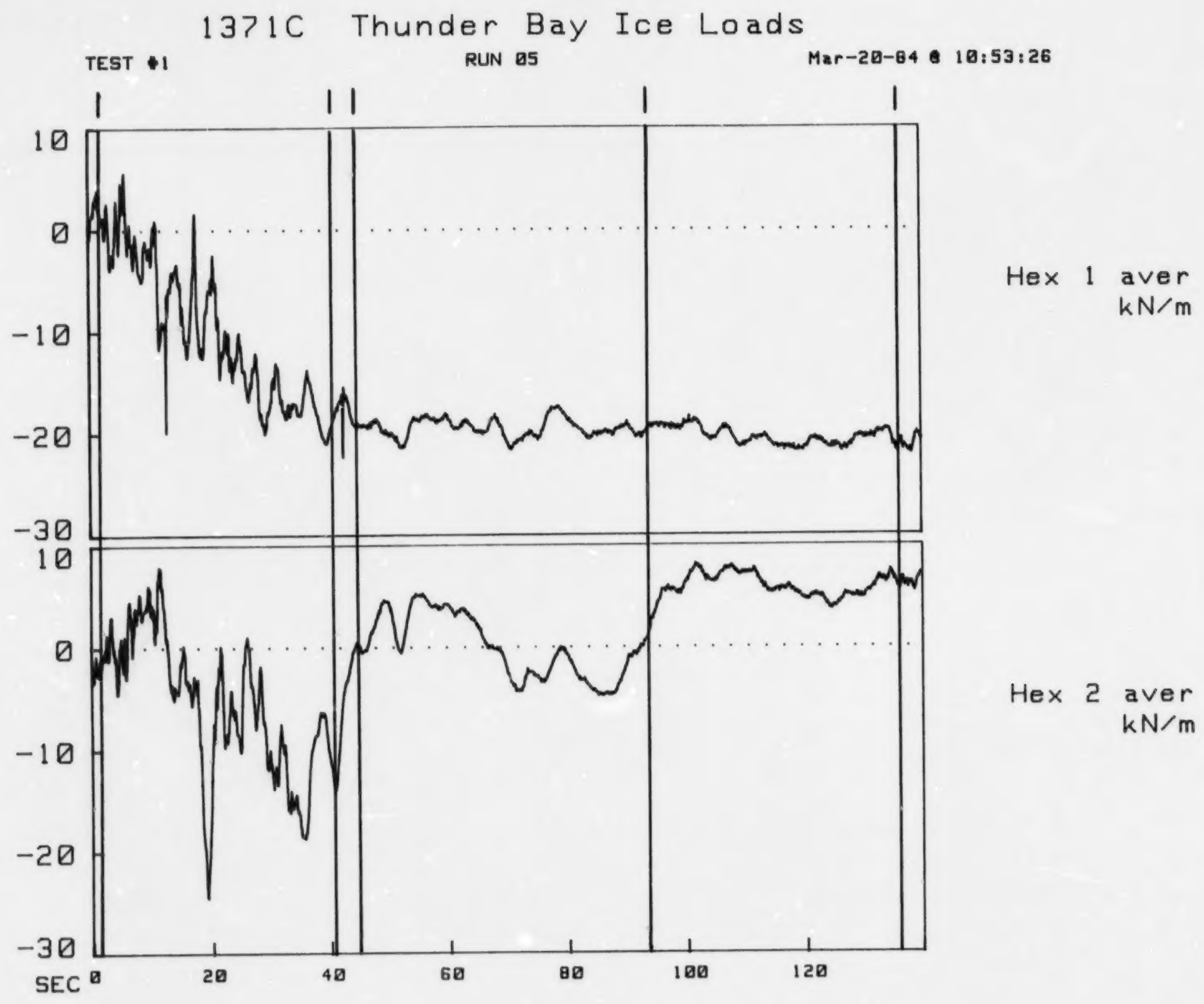


1371C Thunder Bay Ice Loads

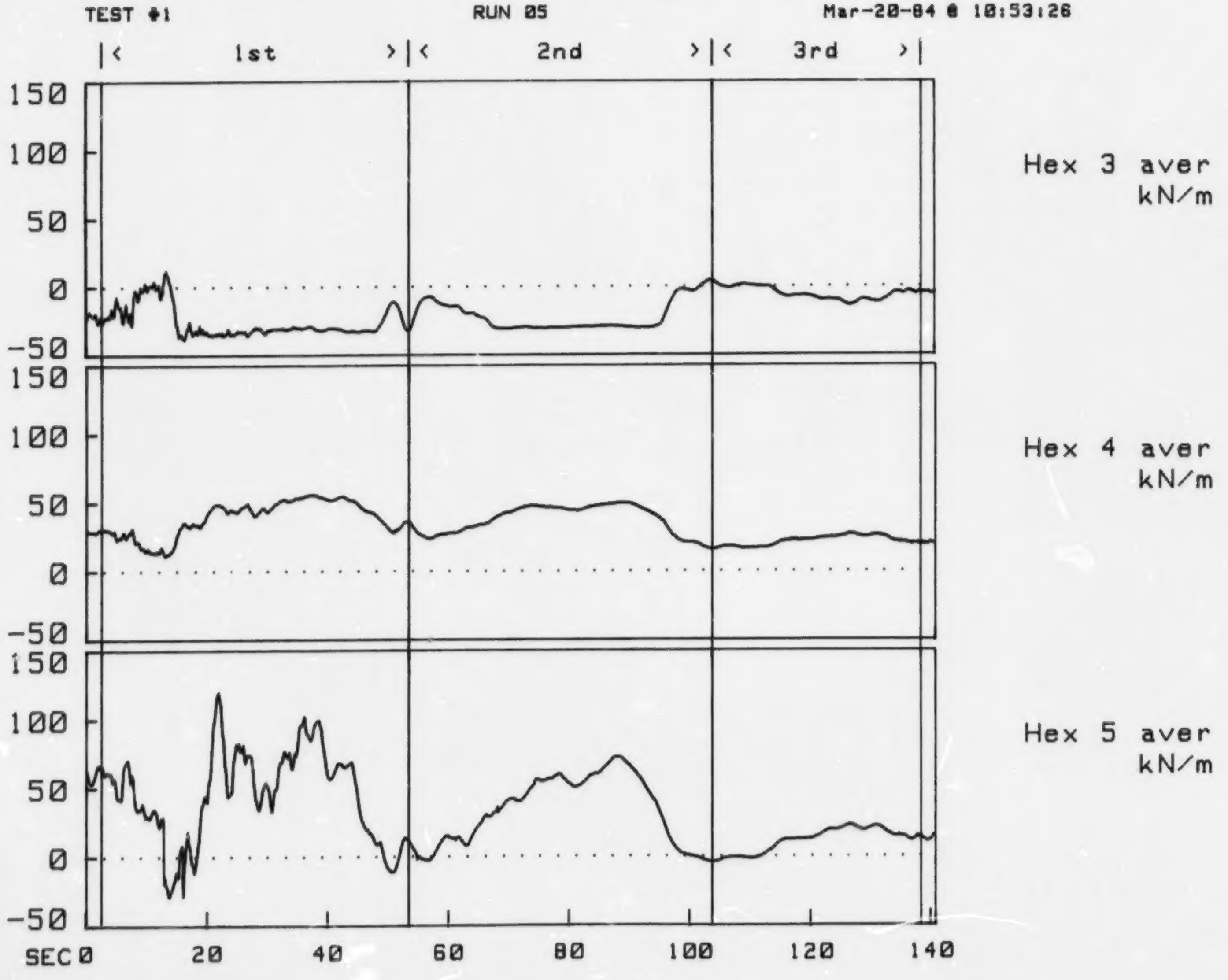


1371C Thunder Bay Ice Loads




1371C Thunder Bay Ice Loads
TEST #1
RUN 05
Mar-20-84 @ 10:53:26
10
0
-10
-20
-30
10
0
-10
-20
-30
SEC
0
20
40
60
80
100
120
Hex 1 aver
kN/m
Hex 2 aver
kN/m

1371C Thunder Bay Ice Loads



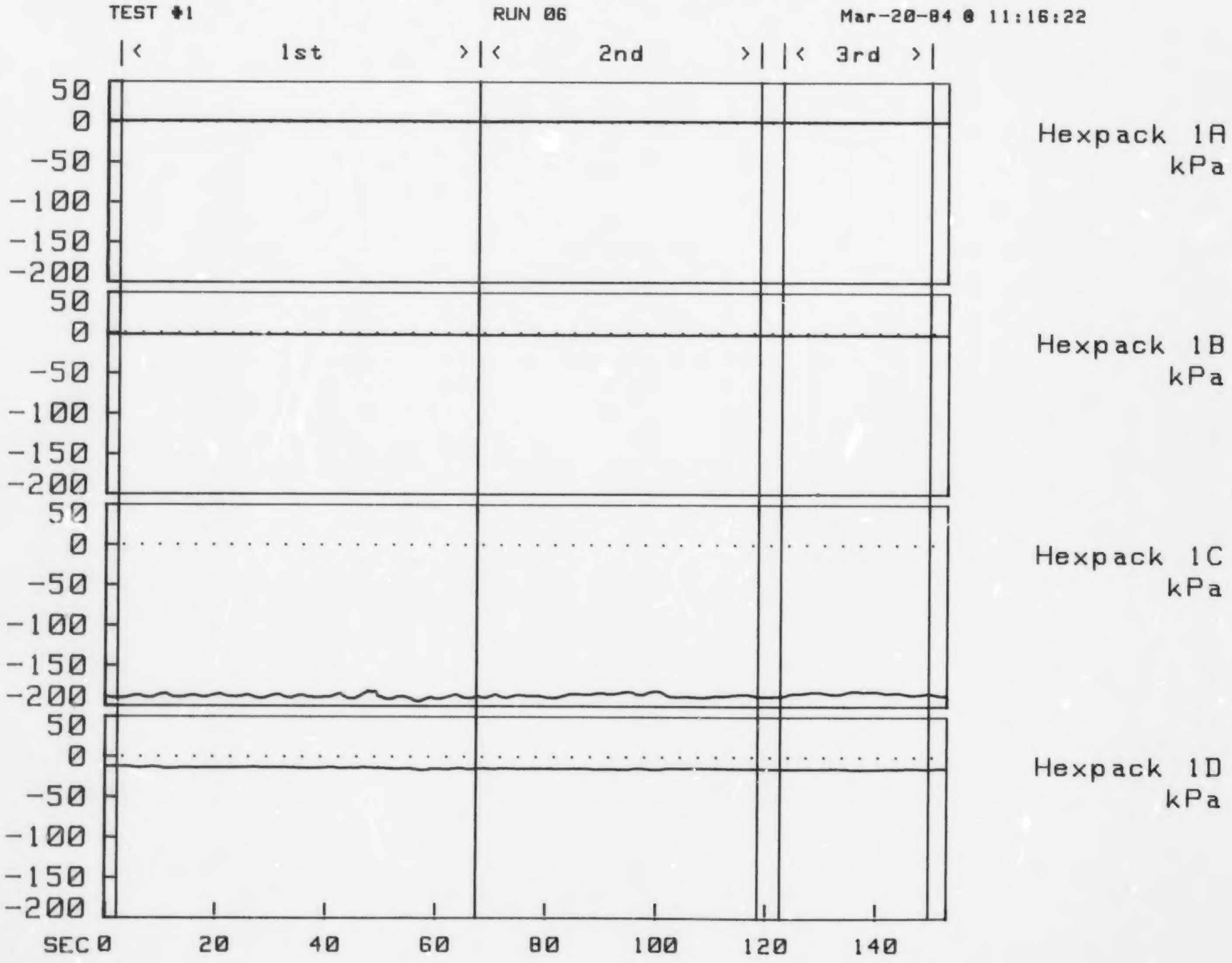
THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	06
Date:	Mar-20-84
Scan Begins at:	11:16:22
Duration of Scan:	150 sec
Scan ends at:	11:18:52
Type of test:	Alexander Henry
Location of Ship:	75 m east of dock Breaking north side of channel

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.84	0.38	kPa
Hex 1B	-1.30	-2.68	kPa
Hex 1C	-180.26	-194.39	kPa
Hex 1D	-11.68	-16.63	kPa
Hex 2A	0.93	-1.74	kPa
Hex 2B	4.18	-105.29	kPa
Hex 2C	29.19	-15.57	kPa
Hex 2D	178.62	76.20	kPa
Hex 3A	3.20	1.52	kPa
Hex 3B	-47.30	-312.51	kPa
Hex 3C	56.41	36.77	kPa
Hex 3D	286.32	117.77	kPa
Hex 4	32.58	18.17	kPa
Hex 5	NA	NA	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	-50.13	-54.90	kN/m
Hex 2 aver	37.55	23.64	kN/m
Hex 3 aver	40.67	0.47	kN/m
Hex 4 aver	65.12	36.34	kN/m
Hex 5 aver	NA	NA	kN/m

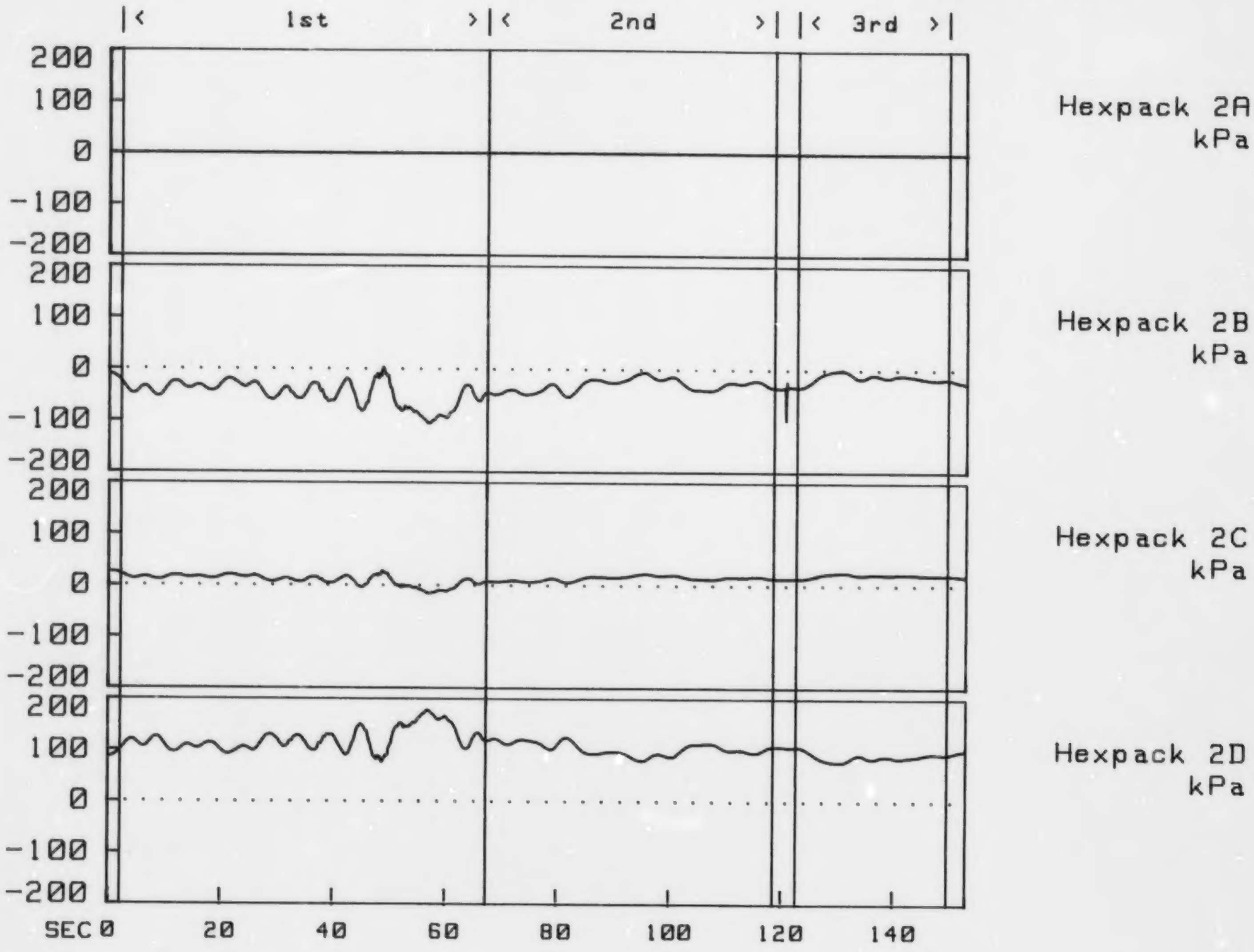
Comments: Hexpack 5 is not functioning.
Hexpack 1 has broken free.

1371C Thunder Bay Ice Loads

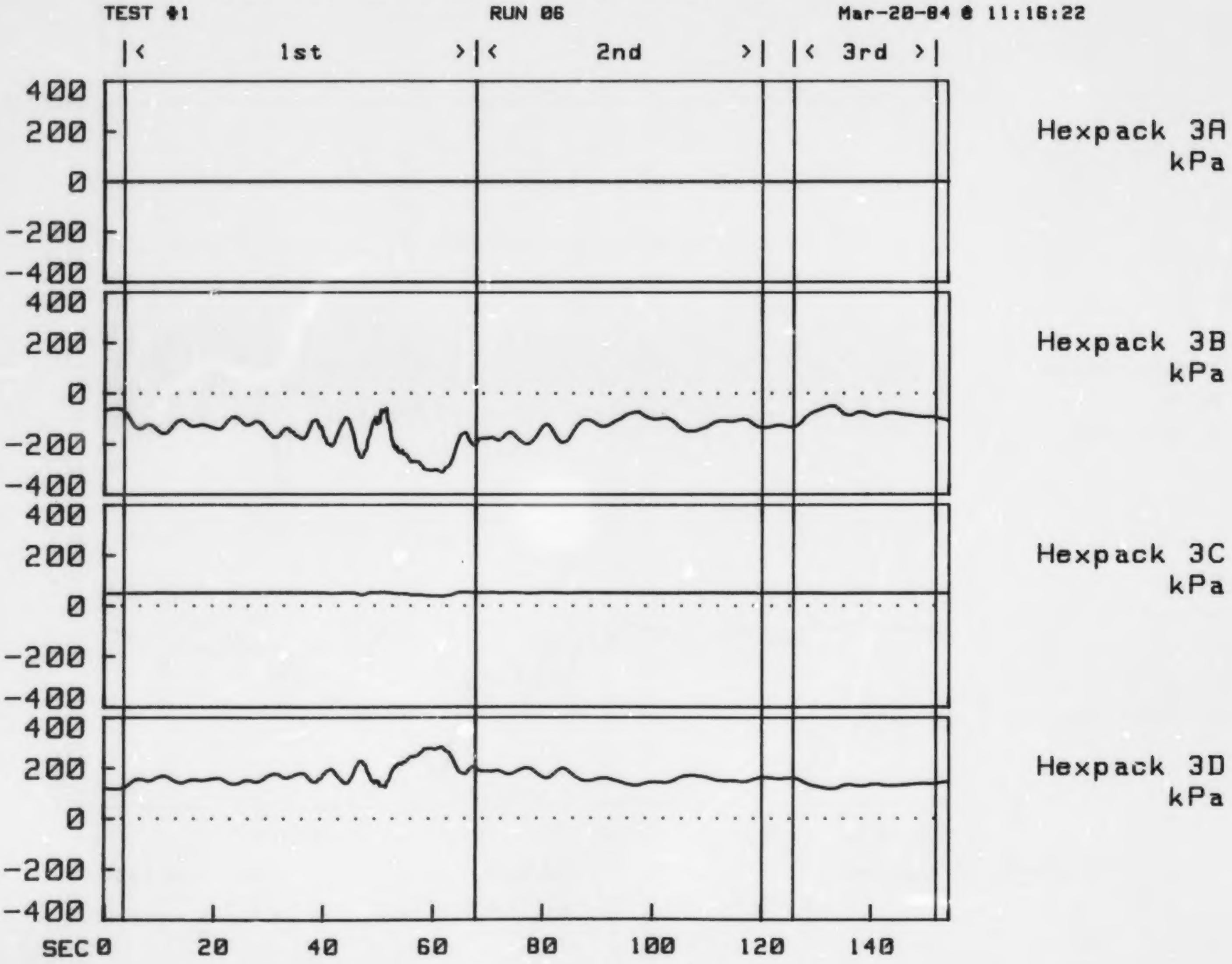


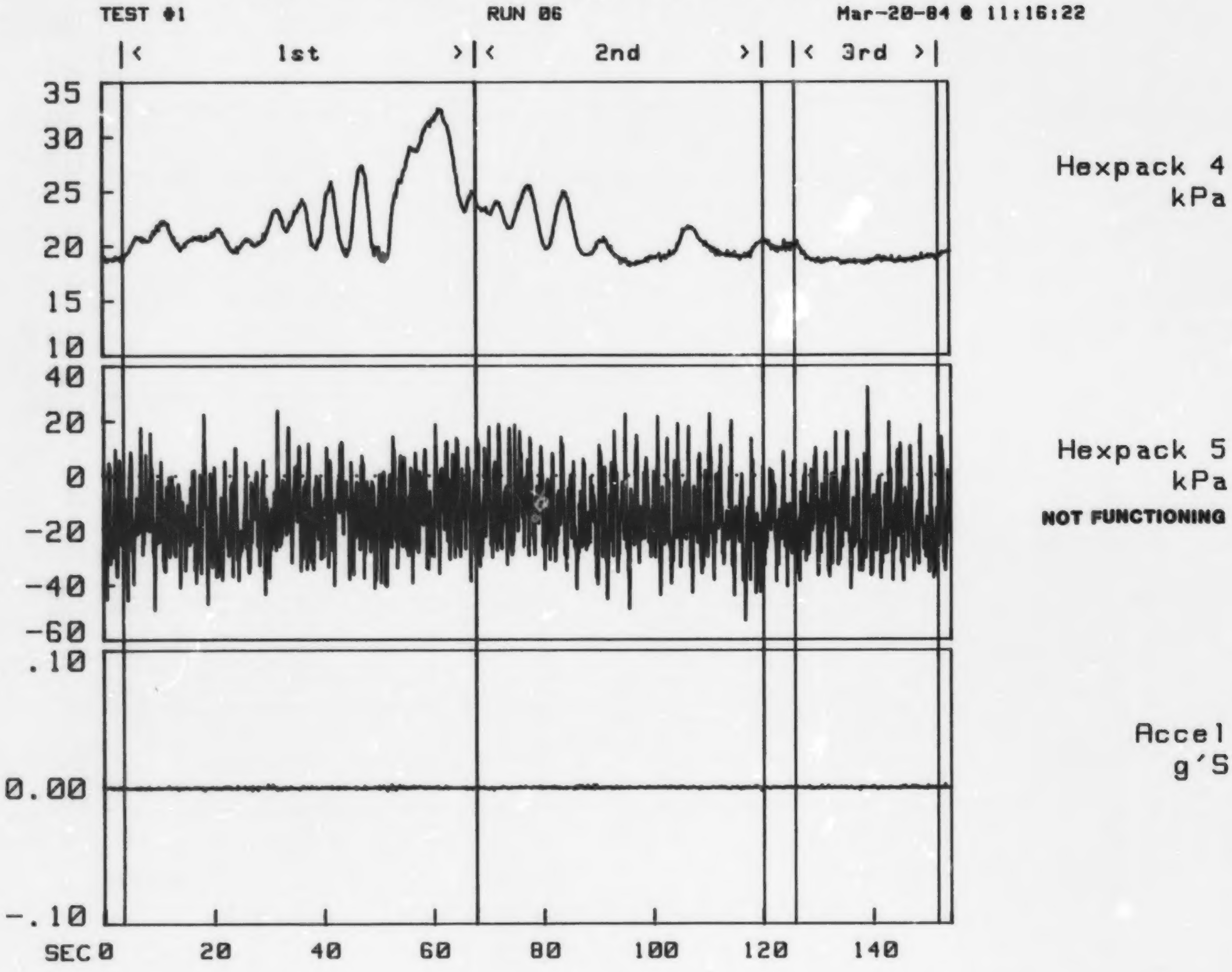
1371C Thunder Bay Ice Loads

TEST #1 RUN 06 Mar-20-84 @ 11:16:22

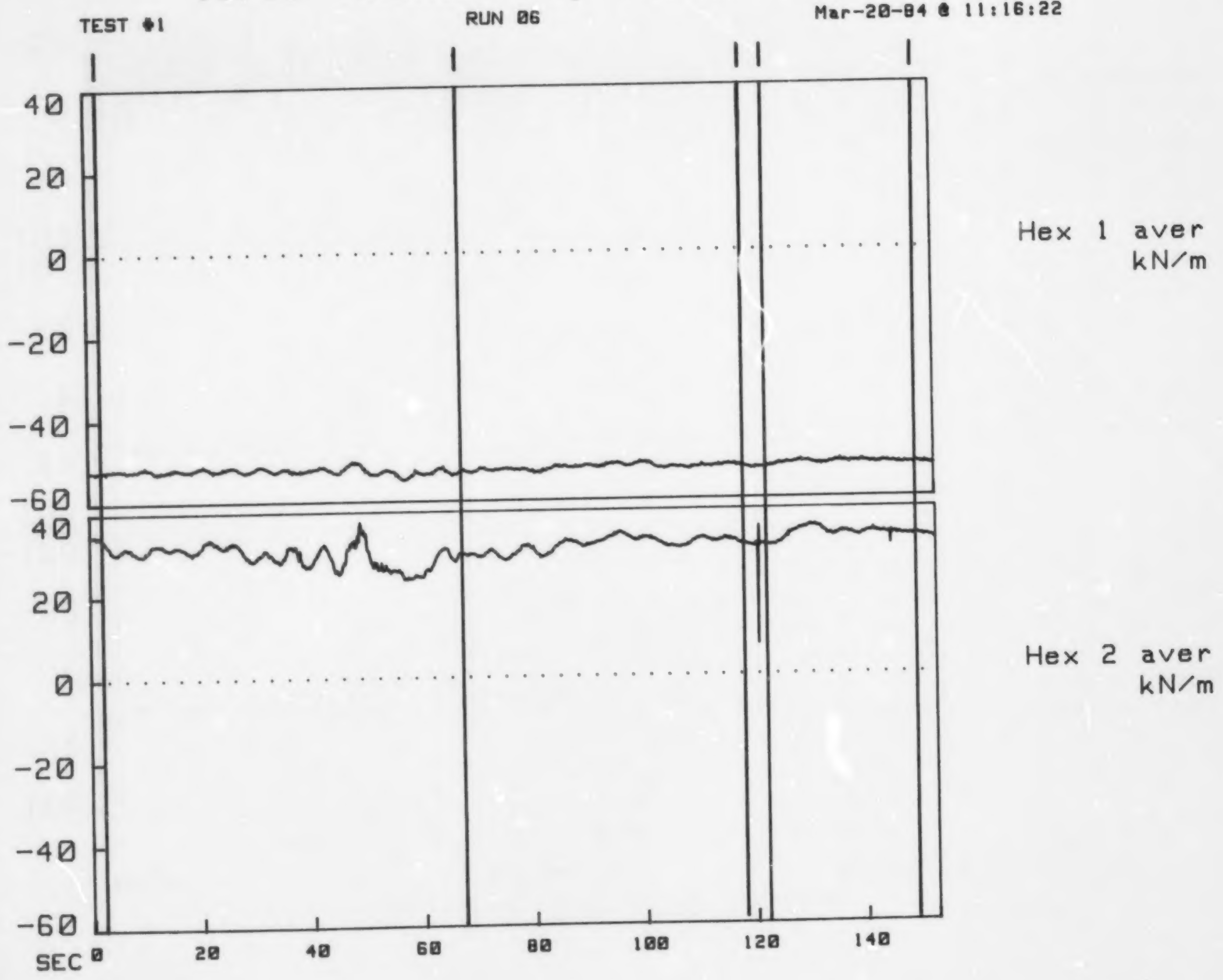


1371C Thunder Bay Ice Loads

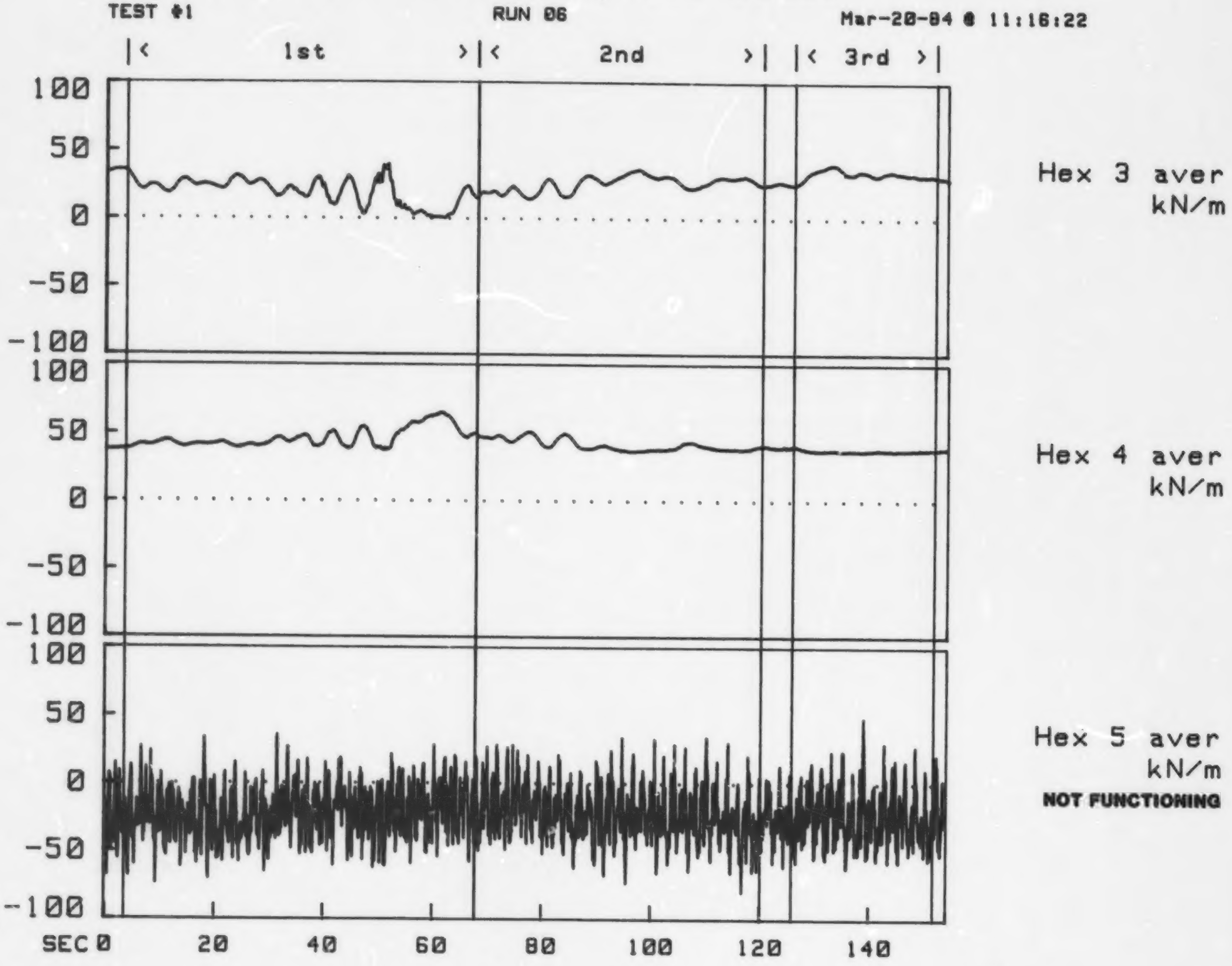



1371C Thunder Bay Ice Loads

1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads



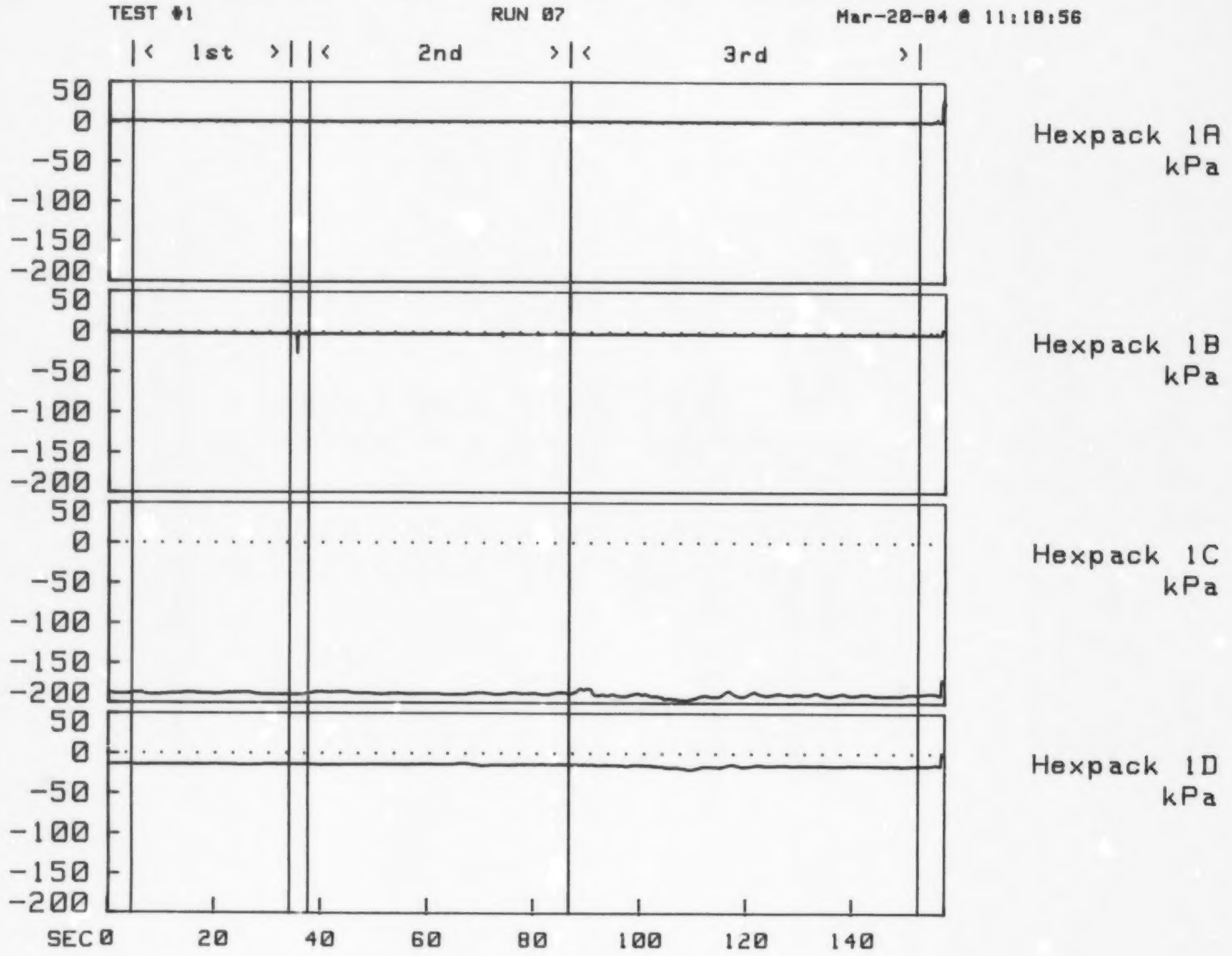
THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	07
Date:	Mar-20-84
Scan Begins at:	11:18:56
Duration of Scan:	150 sec
Scan ends at:	11:21:26
Type of test:	Alexander Henry
Location of Ship:	60 m east of dock Breaking north side of channel

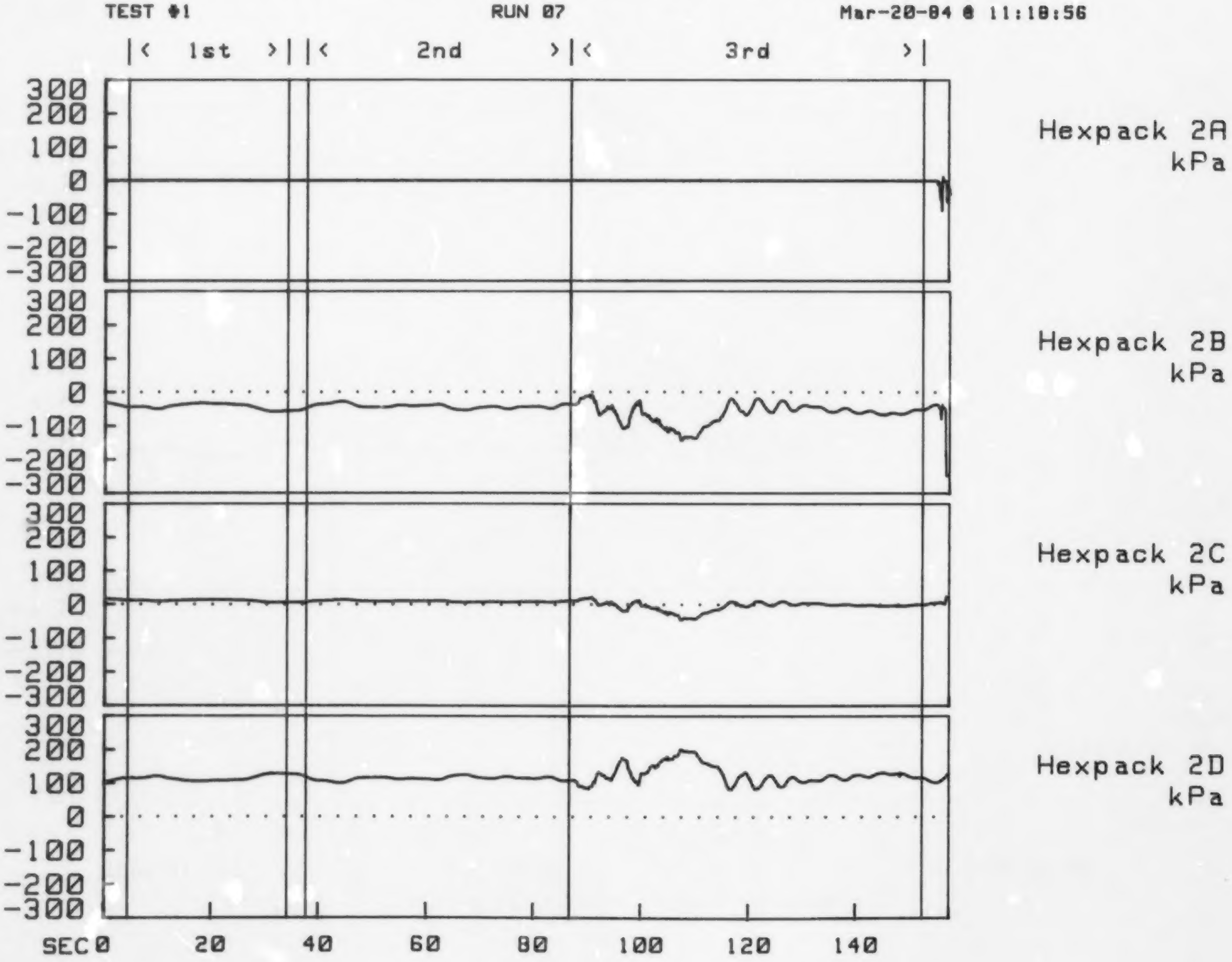
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.93	-0.49	kPa
Hex 1B	-1.21	-5.10	kPa
Hex 1C	-181.32	-197.08	kPa
Hex 1D	-12.11	-20.30	kPa
Hex 2A	1.13	-0.61	kPa
Hex 2B	-6.94	-143.89	kPa
Hex 2C	23.08	-46.08	kPa
Hex 2D	202.52	82.55	kPa
Hex 3A	2.99	1.52	kPa
Hex 3B	-75.46	-369.80	kPa
Hex 3C	54.85	4.97	kPa
Hex 3D	362.93	137.25	kPa
Hex 4	36.14	19.00	kPa
Hex 5	87.69	0.00	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	-50.70	-56.99	kN/m
Hex 2 aver	36.54	10.56	kN/m
Hex 3 aver	38.64	-4.56	kN/m
Hex 4 aver	72.27	37.99	kN/m
Hex 5 aver	131.53	0.00	kN/m

Comments: Hexpack 5 not functioning for first 91 sec. Hexpack 1 has broken free.

1371C Thunder Bay Ice Loads

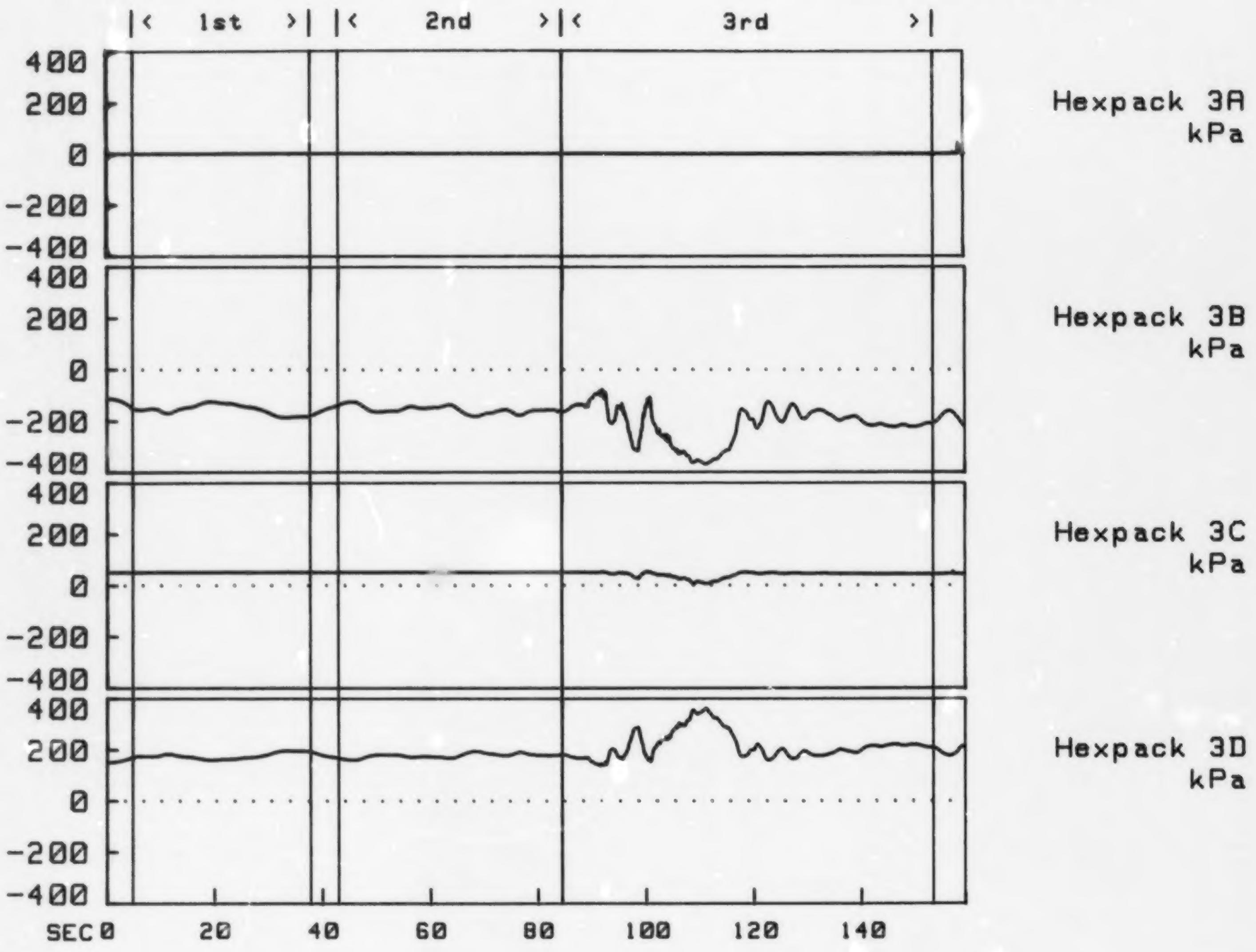


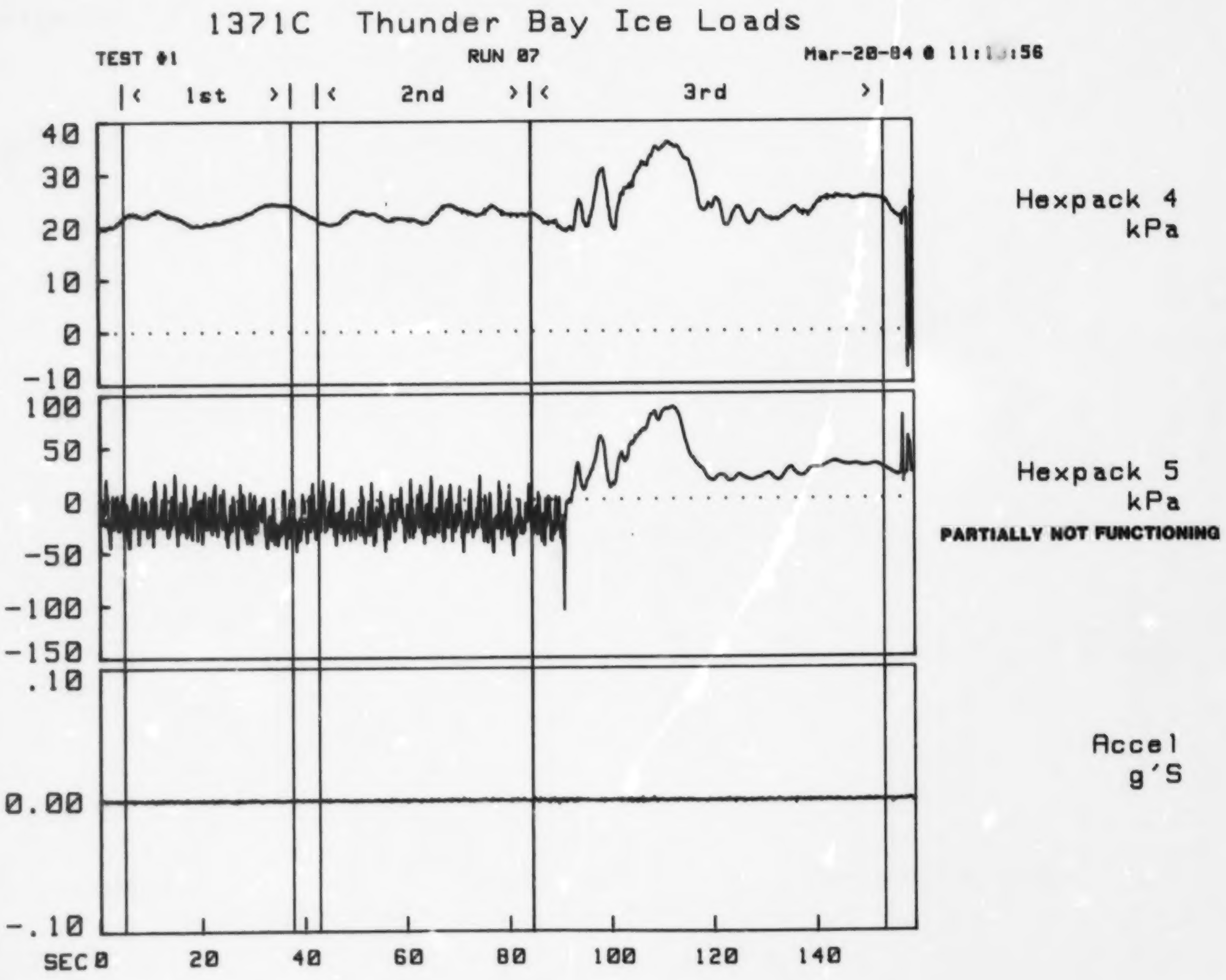
1371C Thunder Bay Ice Loads

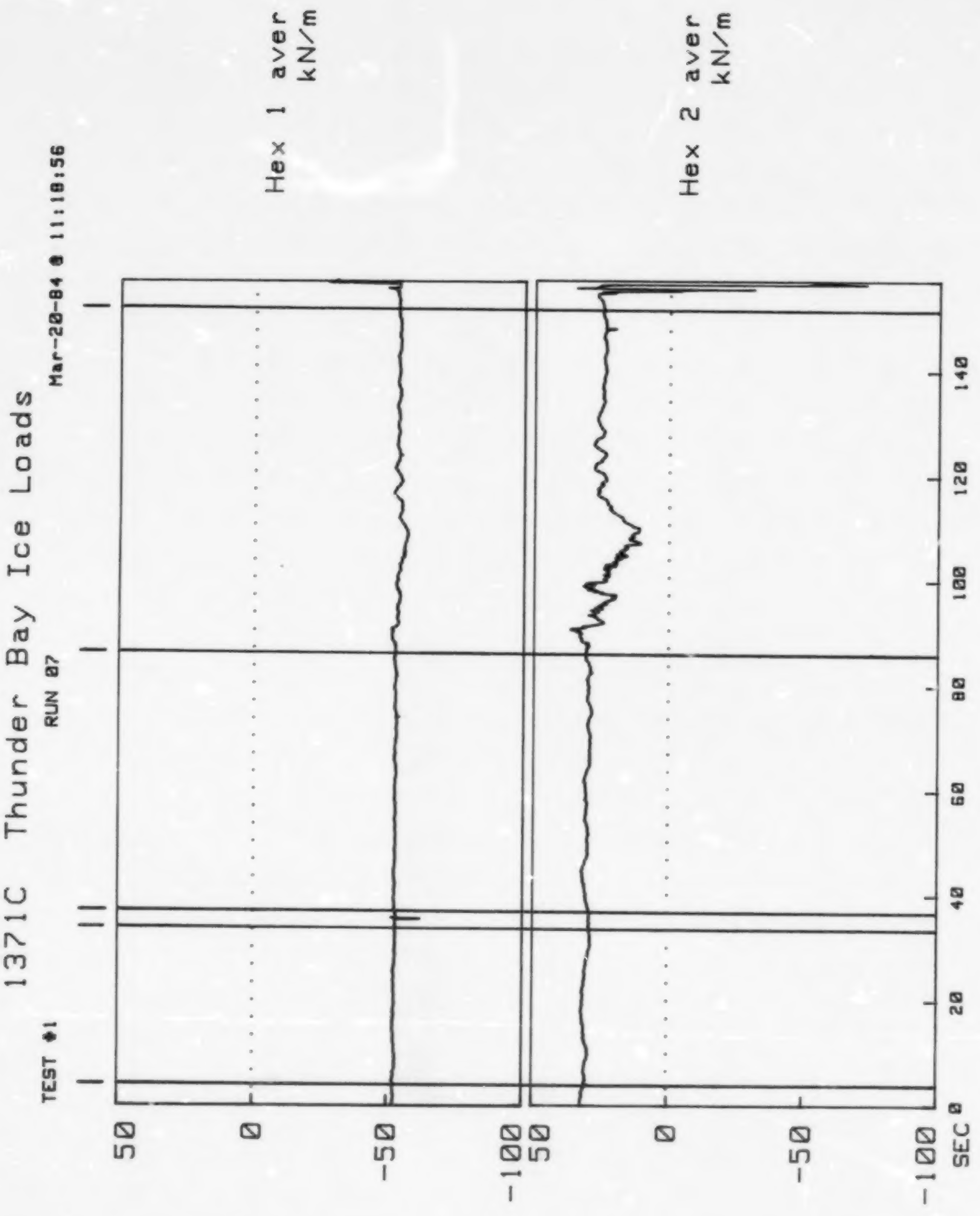


1371C Thunder Bay Ice Loads

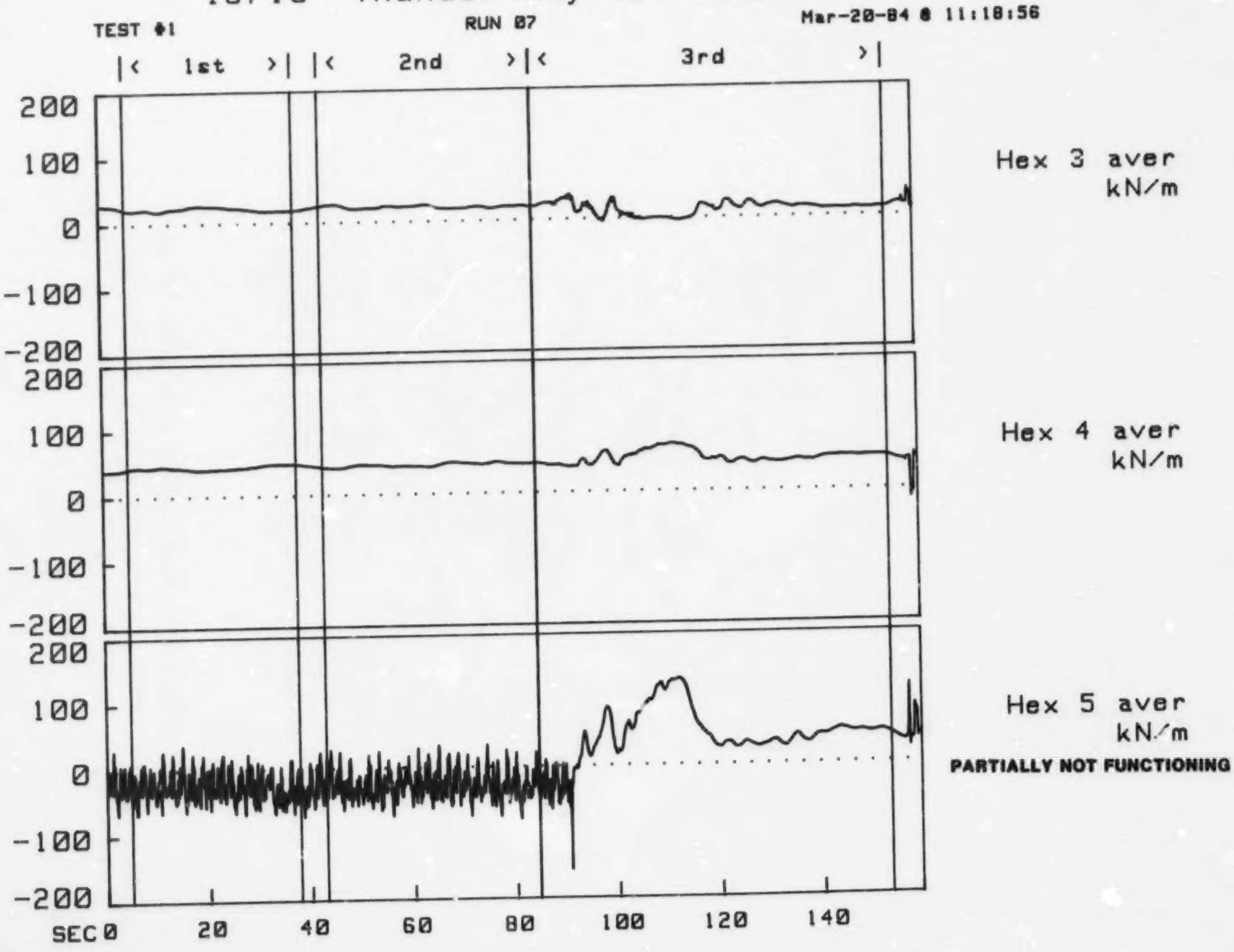
TEST #1 RUN 07 Mar-20-84 @ 11:18:56




1371C Thunder Bay Ice Loads
TEST #1
RUN 07
Mar-20-84 @ 11:[illegible]:56
|< 1st >|
|< 2nd >|
|< 3rd >|
40
30
20
10
0
-10
Hexpack 4
kPa
100
50
0
-50
-100
-150
Hexpack 5
kPa
PARTIALLY NOT FUNCTIONING
.10
0.00
-.10
Accel
g'S
SEC 0
20
40
60
80
100
120
140


TEST #1
1371C Thunder Bay Ice Loads
RUN 07
Mar-20-84 @ 11:18:56
Hex 1 aver
kN/m
Hex 2 aver
kN/m
50
0
-50
-100
50
0
-50
-100
SEC 0
20
40
60
80
100
120
140

1371C Thunder Bay Ice Loads



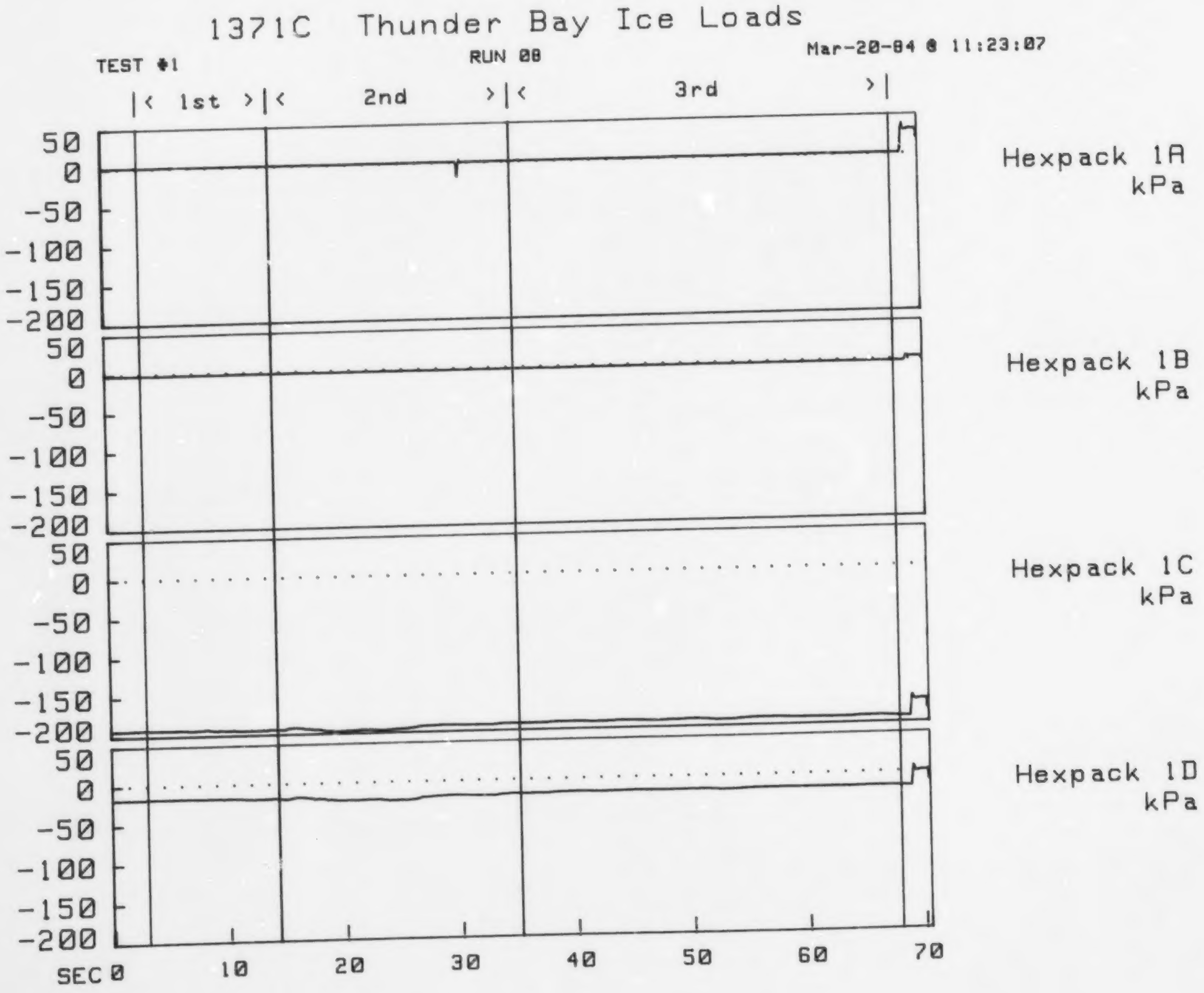
PARTIALLY NOT FUNCTIONING

THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	1
Run #:	08
Date:	Mar-20-84
Scan Begins at:	11:23:07
Duration of Scan:	70 sec
Scan ends at:	11:24:17
Type of test:	Alexander Henry
Location of Ship:	45 m east of dock Breaking north side of channel

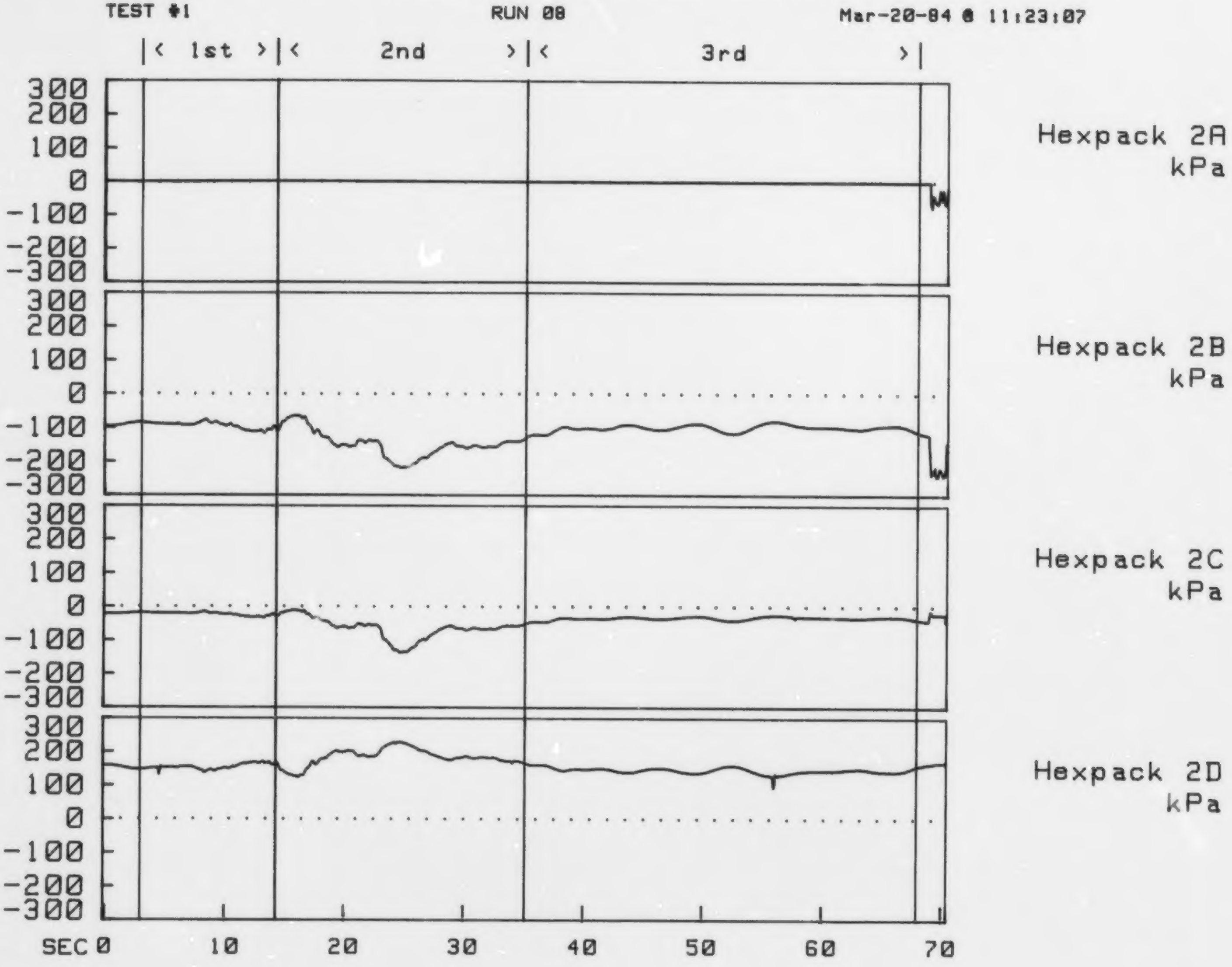
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.84	-0.49	kPa
Hex 1B	-1.65	-2.68	kPa
Hex 1C	-190.16	-197.66	kPa
Hex 1D	-16.31	-23.75	kPa
Hex 2A	0.83	-0.61	kPa
Hex 2B	-62.63	-218.50	kPa
Hex 2C	-9.99	-137.16	kPa
Hex 2D	229.51	125.31	kPa
Hex 3A	2.78	1.42	kPa
Hex 3B	-223.52	-432.21	kPa
Hex 3C	45.12	-58.12	kPa
Hex 3D	471.95	223.28	kPa
Hex 4	37.38	25.46	kPa
Hex 5	122.33	22.73	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	-53.82	-64.87	kN/m
Hex 2 aver	22.04	-30.50	kN/m
Hex 3 aver	12.35	-14.12	kN/m
Hex 4 aver	74.76	50.91	kN/m
Hex 5 aver	183.49	34.09	kN/m

Comments: A communication spike after 70 sec.


1371C Thunder Bay Ice Loads
TEST #1
RUN 08
Mar-20-84 @ 11:23:07
|< 1st >|< 2nd >|< 3rd >|
Hexpack 1A kPa
Hexpack 1B kPa
Hexpack 1C kPa
Hexpack 1D kPa
50
0
-50
-100
-150
-200
SEC 0
10
20
30
40
50
60
70

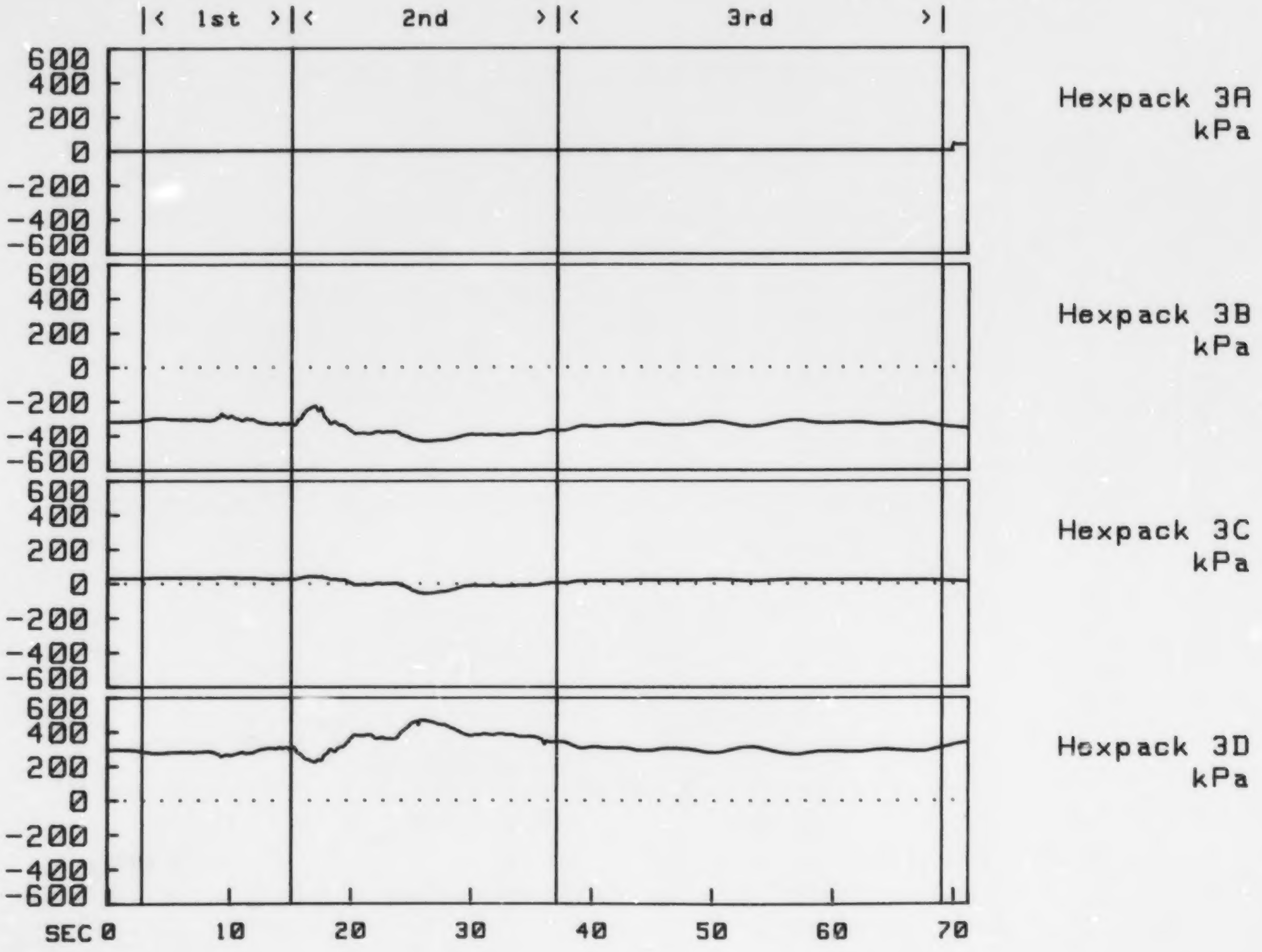
1371C Thunder Bay Ice Loads

TEST #1 RUN 08 Mar-20-84 @ 11:23:07

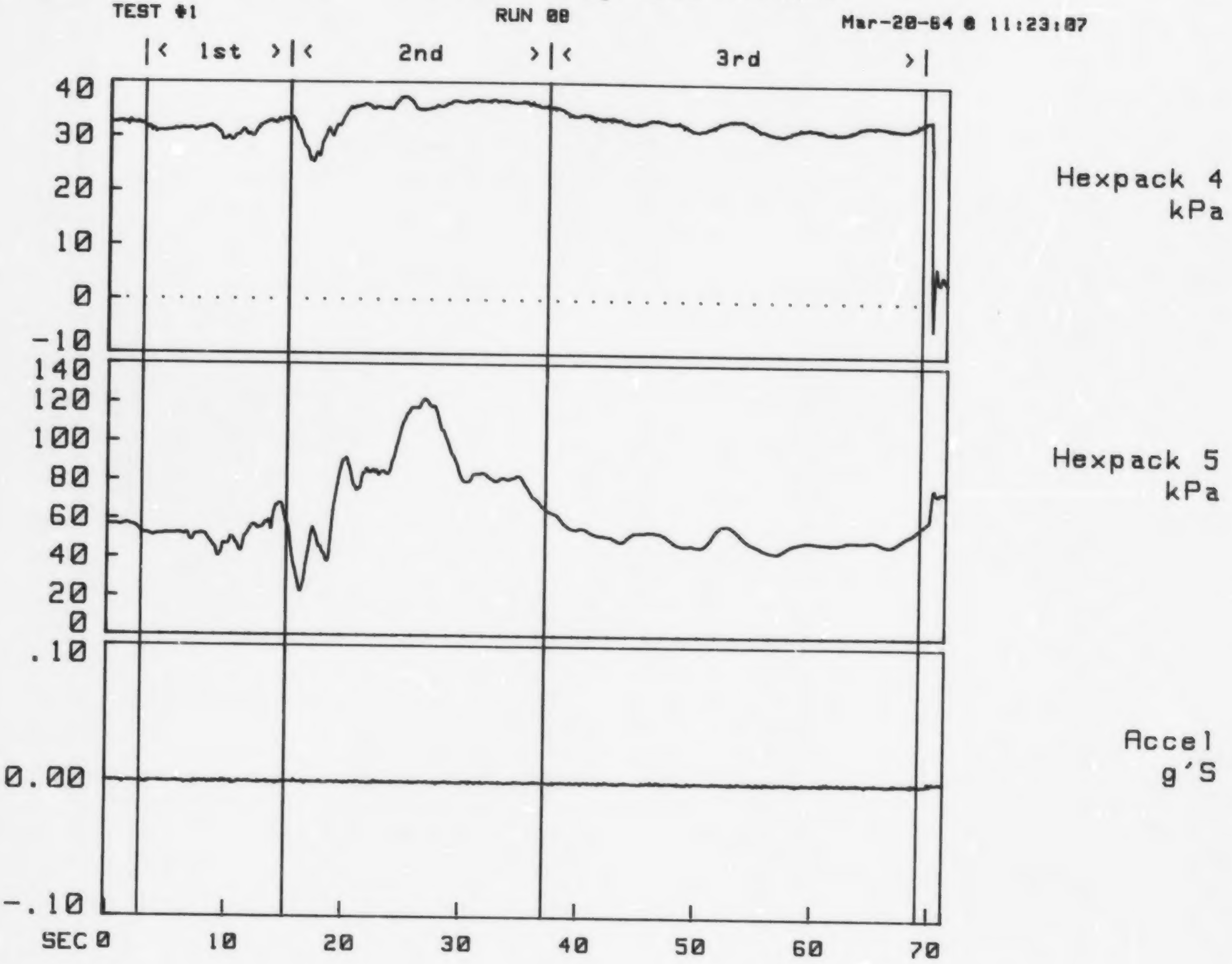


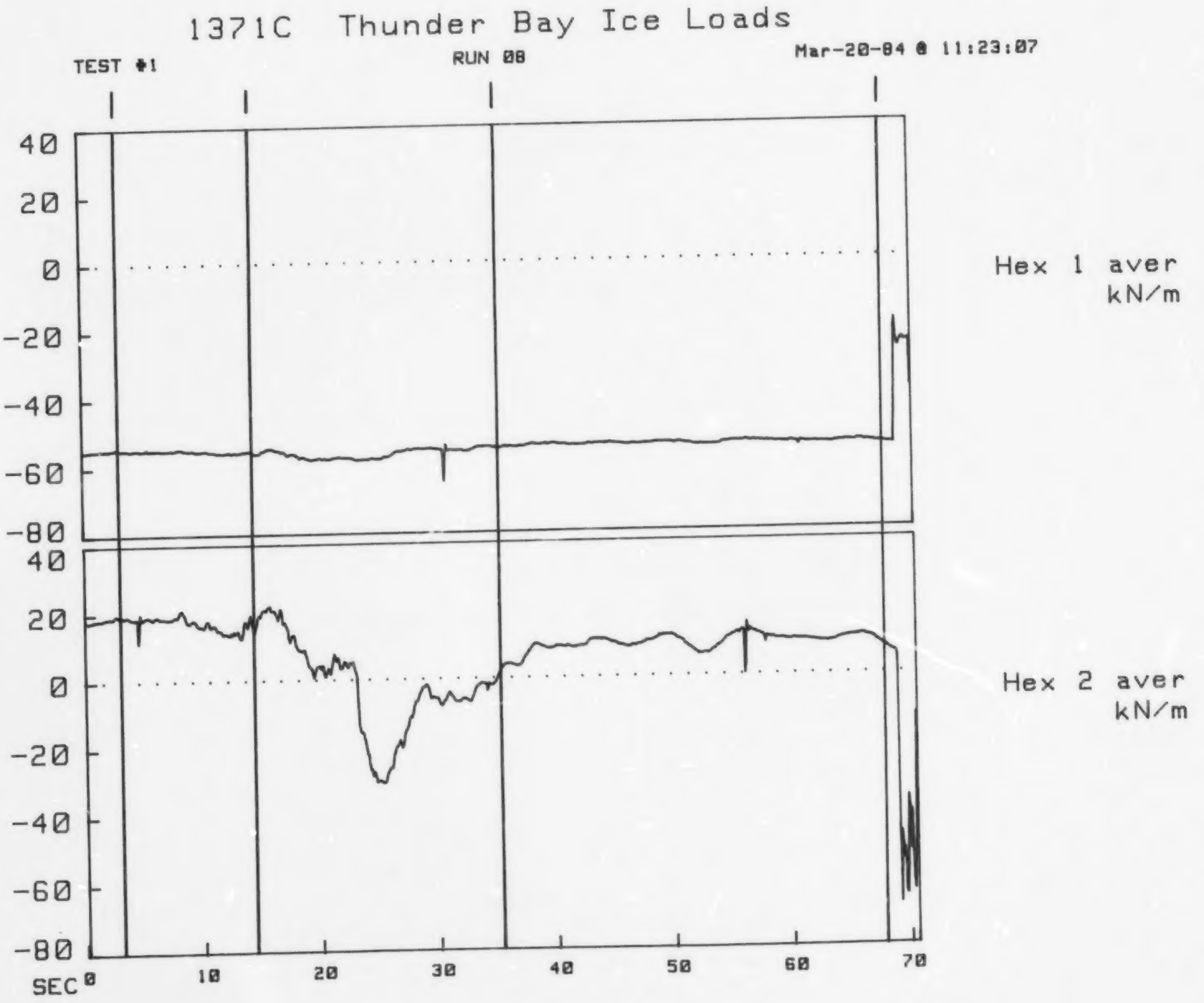
1371C Thunder Bay Ice Loads

TEST #1 RUN 08 Mar-20-84 @ 11:23:07

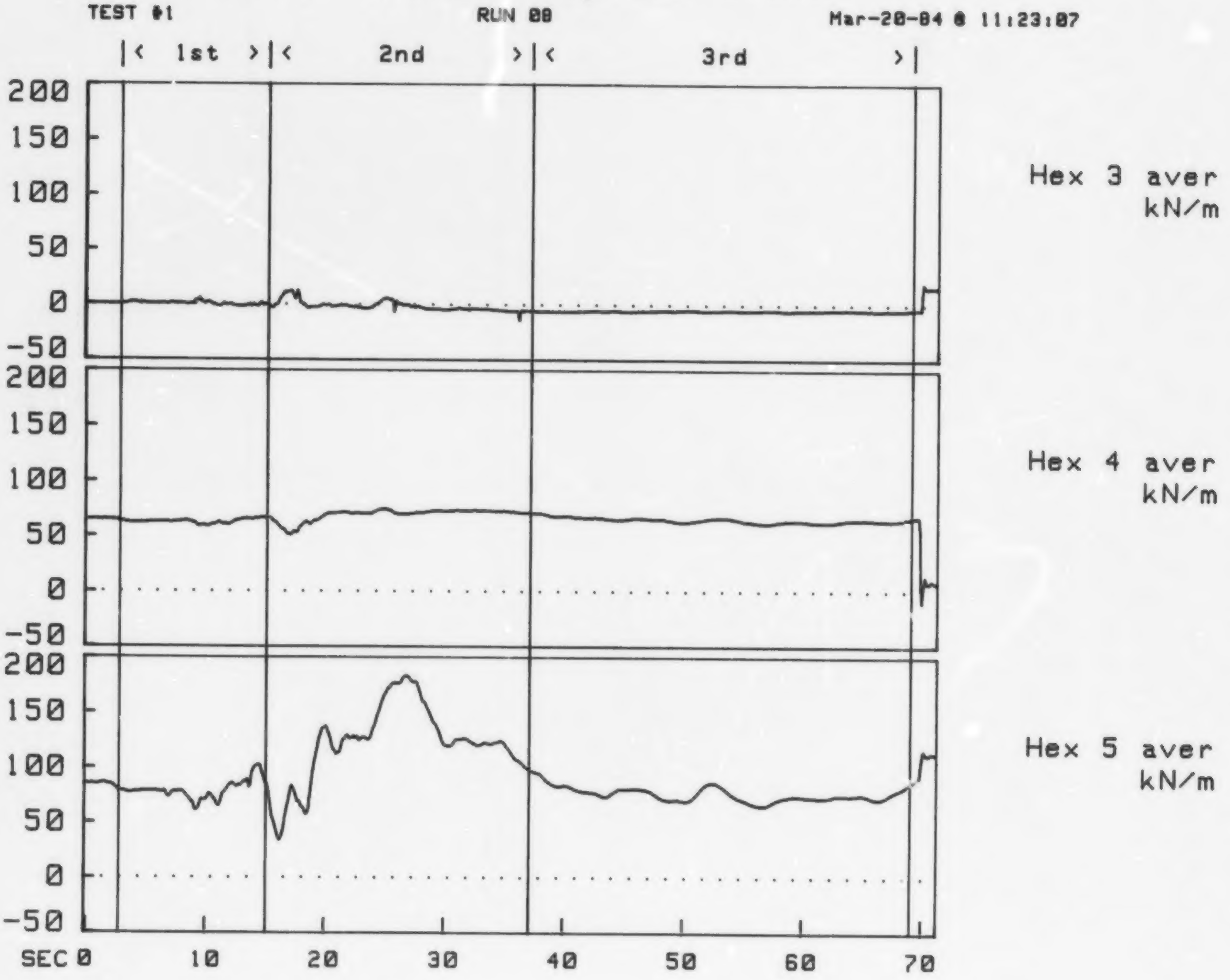


1371C Thunder Bay Ice Loads




1371C Thunder Bay Ice Loads
TEST #1
RUN 08
Mar-20-84 @ 11:23:07
Hex 1 aver
kN/m
Hex 2 aver
kN/m
40
20
0
-20
-40
-60
-80
SEC
0
10
20
30
40
50
60
70

1371C Thunder Bay Ice Loads



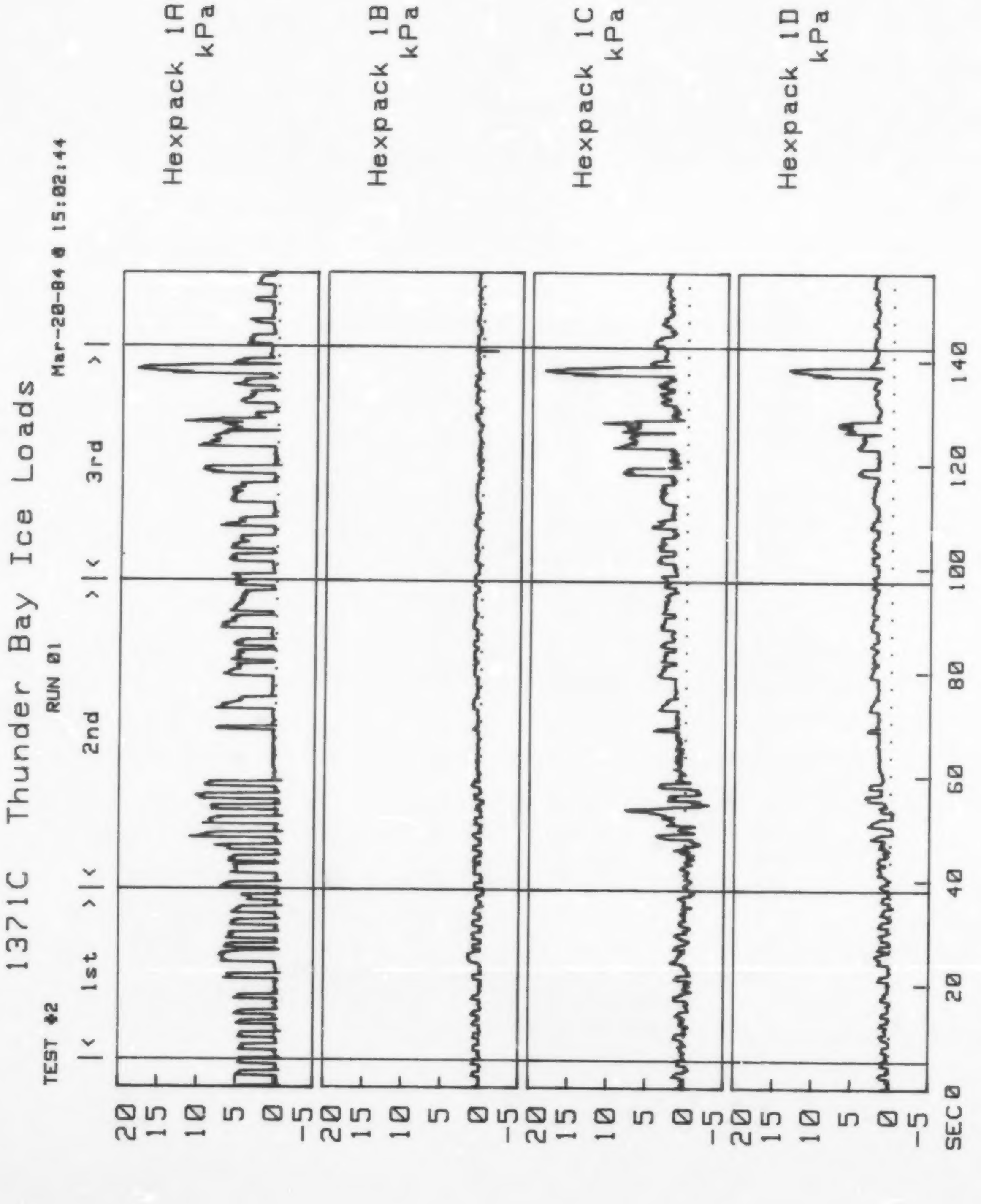
THUNDER BAY ICE LOAD TEST SUMMARY

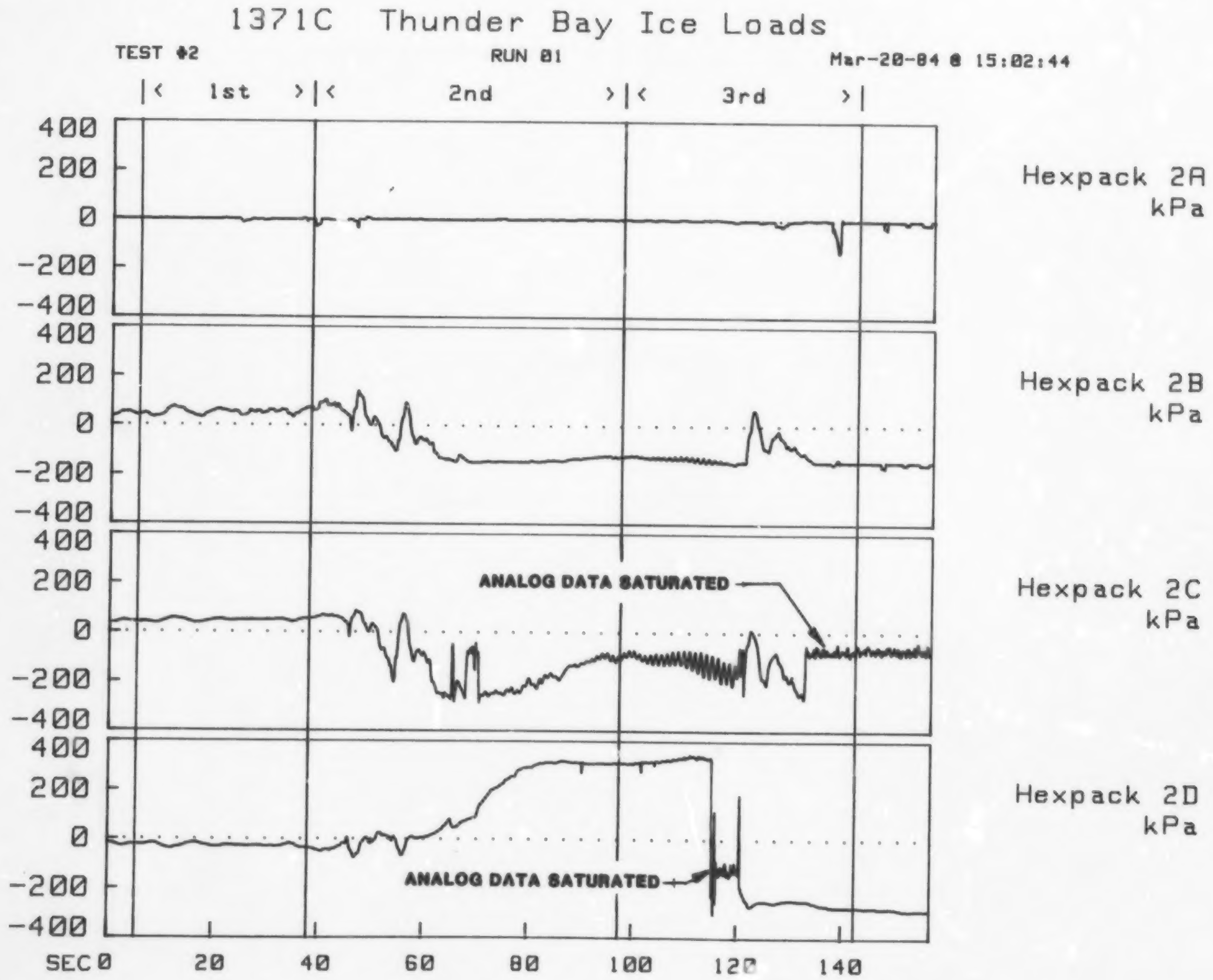
Test #:	2
Run #:	01
Date:	Mar-20-84
Scan Begins at:	15:02:44
Duration of Scan:	150 sec
Scan ends at:	15:05:14
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 15 m east of dock Ends 20 m inside dock Ramming unbroken ice

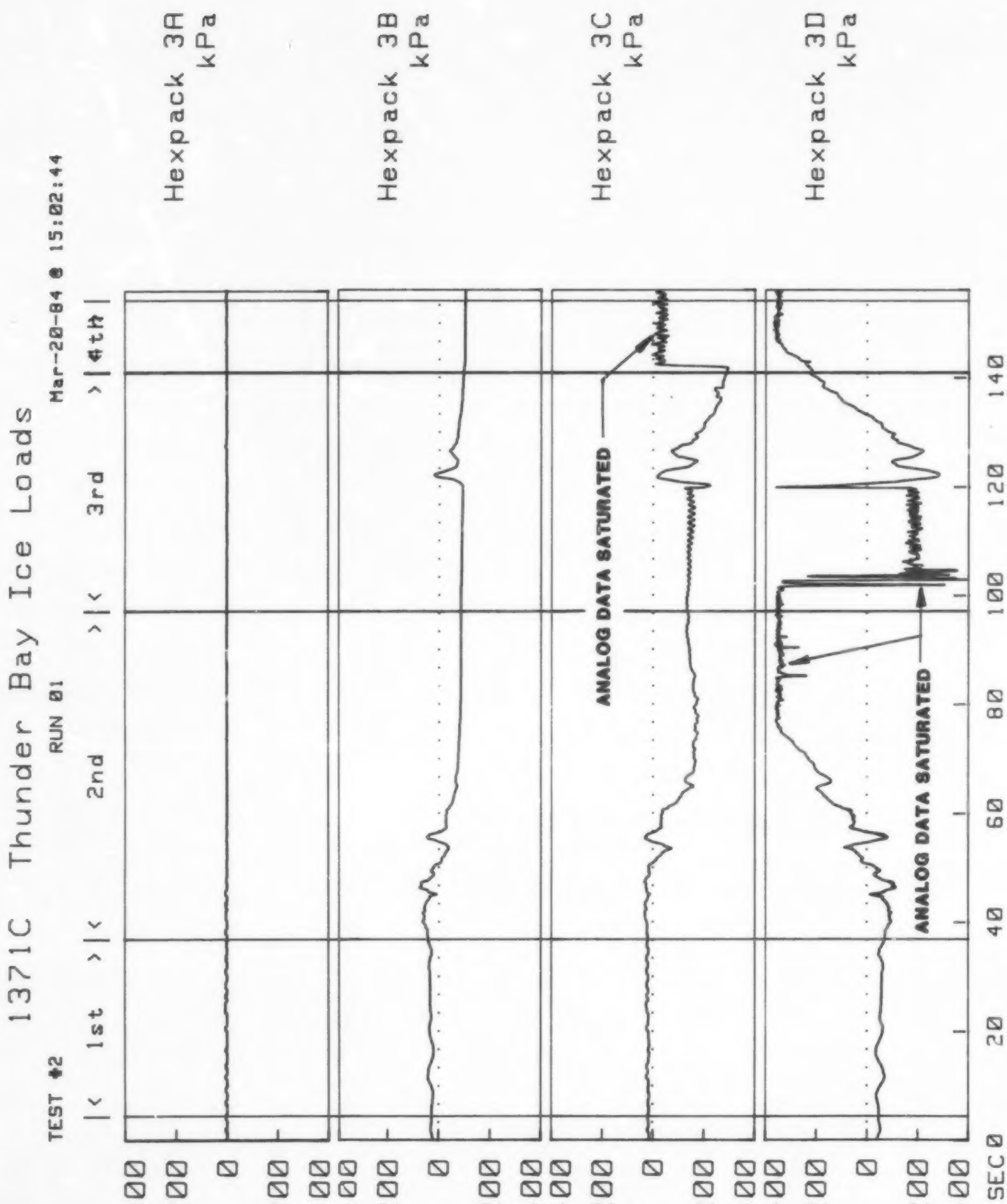
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	1.29	0.00	kPa
Hex 1B	0.79	0.00	kPa
Hex 1C	2.51	-0.72	kPa
Hex 1D	2.08	-0.65	kPa
Hex 2A	5.19	-15.03	kPa
Hex 2B	140.73	-155.41	kPa
Hex 2C	87.97	-285.78	kPa
Hex 2D	347.97	-299.82	kPa
Hex 3A	7.63	-1.48	kPa
Hex 3B	77.28	-103.07	kPa
Hex 3C	36.10	-296.20	kPa
Hex 3D	370.80	-289.86	kPa
Hex 4	12.74	-99.12	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	5.04	-0.98	kN/m
Hex 2 aver	65.00*	-280.00*	kN/m
Hex 3 aver	125.00*	-119.15	kN/m
Hex 4 aver	25.49	-198.25	kN/m

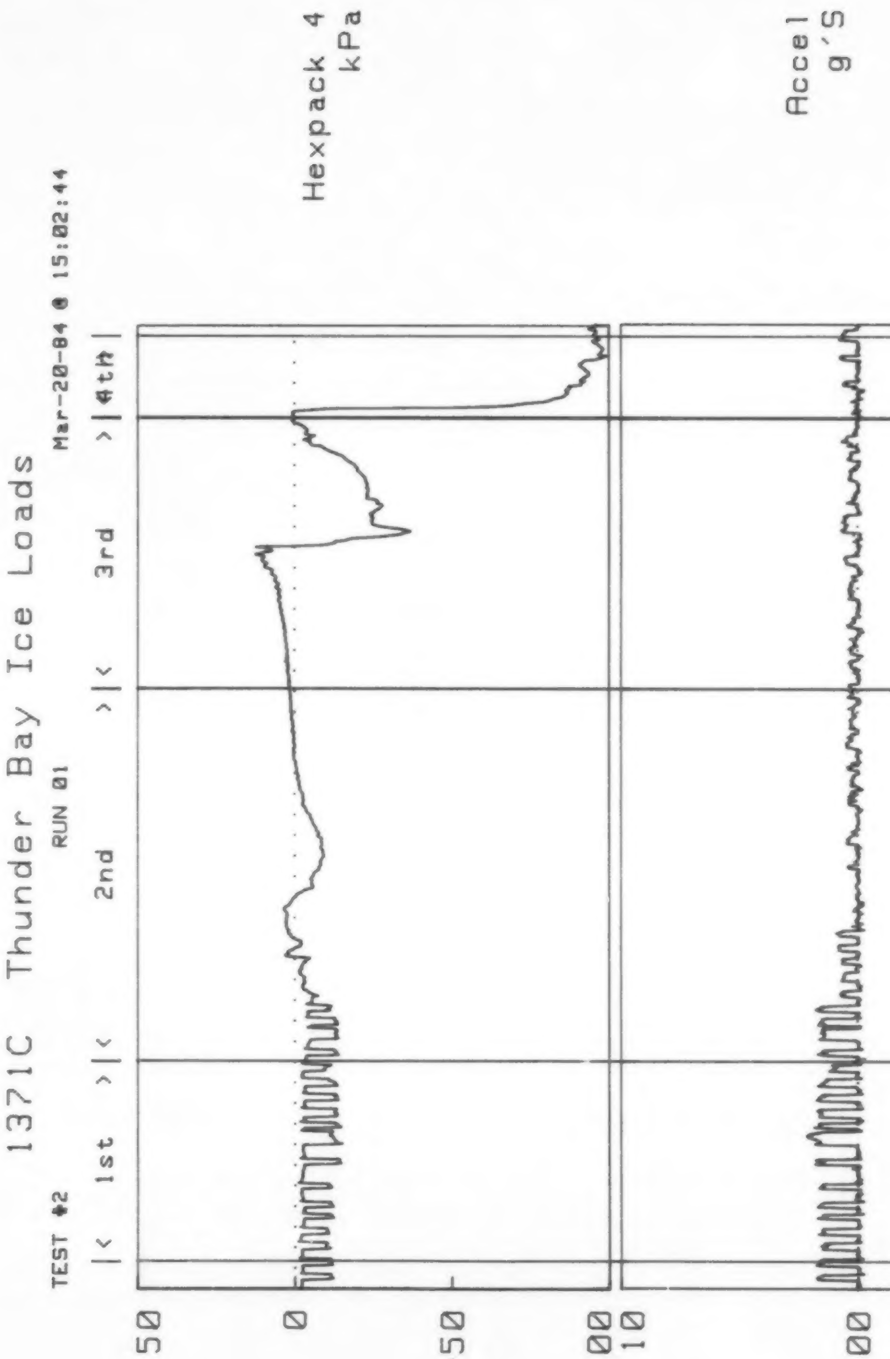
Comments: Periodic communication throughout. Hexpack 2C, 2D, 3C & 3D saturated the analog record.

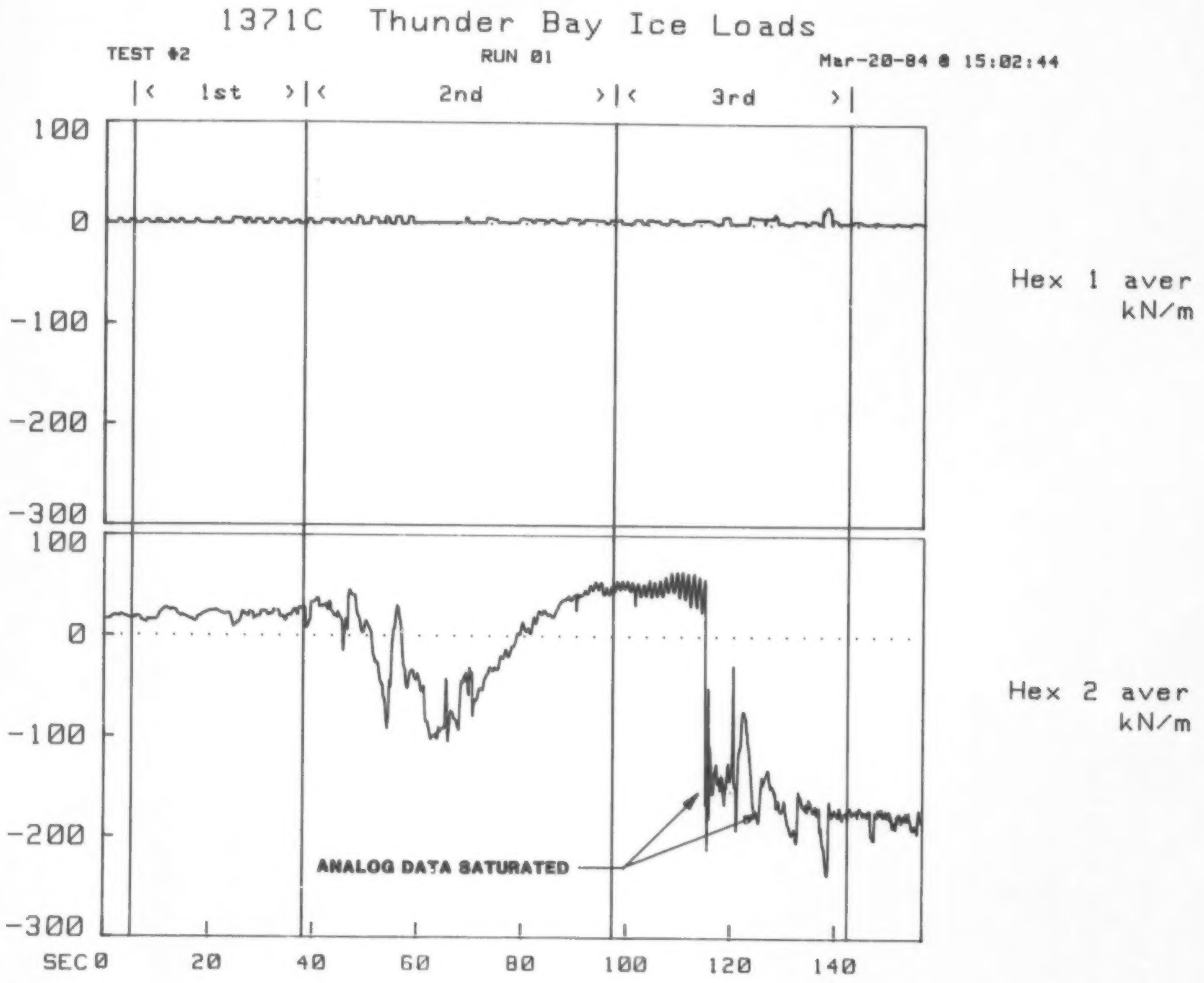
* Estimated


1371C Thunder Bay Ice Loads
TEST #2
RUN 01
Mar-20-84 @ 15:02:44
|< 1st >|< 2nd >|< 3rd >|
Hexpack 1A kPa
Hexpack 1B kPa
Hexpack 1C kPa
Hexpack 1D kPa
20
15
10
5
0
-5
SEC 0
20
40
60
80
100
120
140

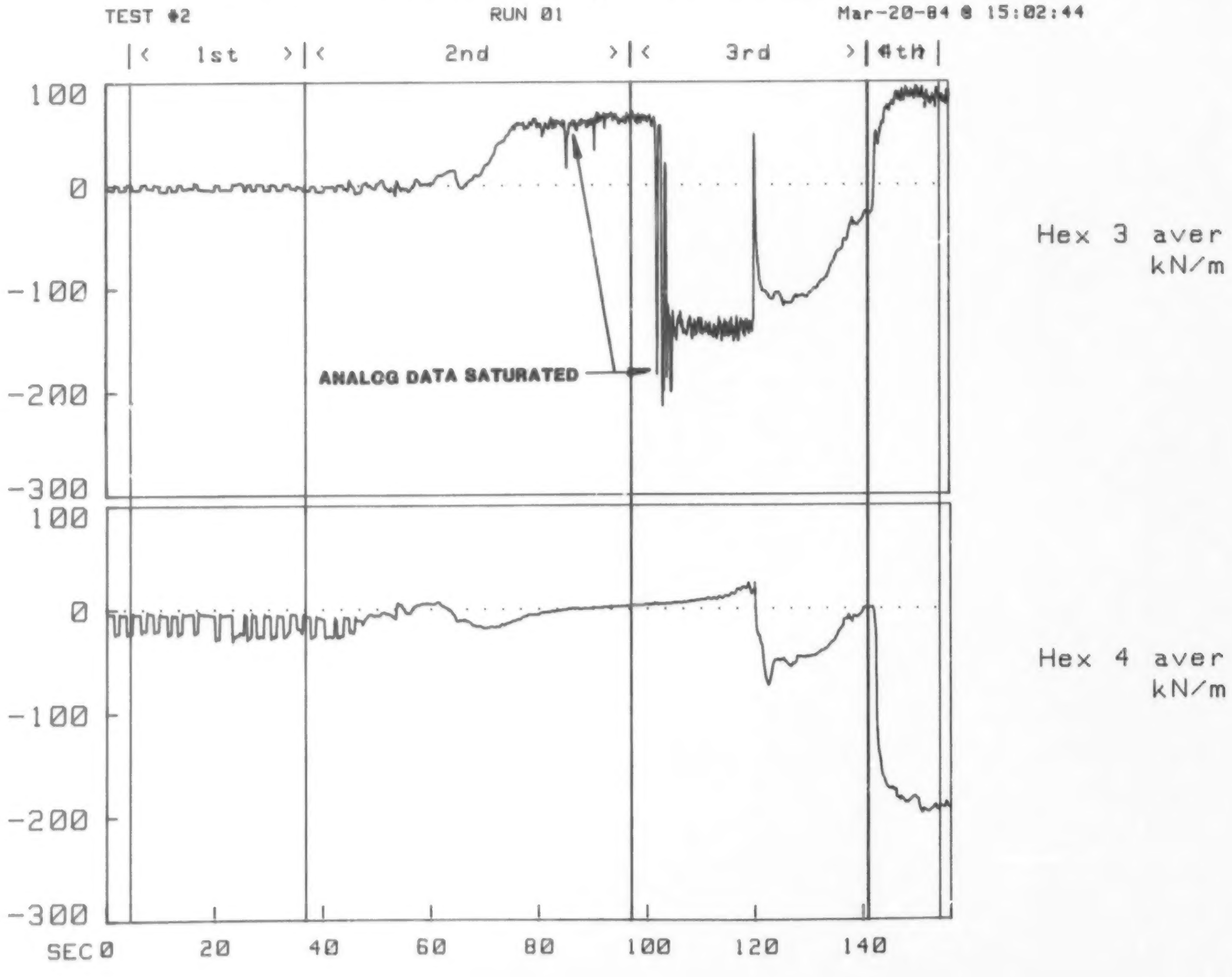

1371C Thunder Bay Ice Loads
TEST #2
RUN 01
Mar-20-84 @ 15:02:44
|< 1st >|< 2nd >|< 3rd >|
400
200
0
-200
-400
Hexpack 2A
kPa
Hexpack 2B
kPa
ANALOG DATA SATURATED
Hexpack 2C
kPa
ANALOG DATA SATURATED
Hexpack 2D
kPa
SEC 0
20
40
60
80
100
120
140


1371C Thunder Bay Ice Loads
TEST #2
RUN 01
Mar-20-84 @ 15:02:44
|< 1st >|< 2nd >|< 3rd >|4th|
Hexpack 3A kPa
Hexpack 3B kPa
Hexpack 3C kPa
Hexpack 3D kPa
400
200
0
-200
-400
SEC 0
20
40
60
80
100
120
140
ANALOG DATA SATURATED
ANALOG DATA SATURATED


1371C Thunder Bay Ice Loads
TEST #2
RUN 01
Mar-20-84 @ 15:02:44
|< 1st >|< 2nd >|< 3rd >|< 4th >|
Hexpack 4
kPa
Accel
g'S
50
0
-50
-100
.10
0.00
-.10
SEC0
20
40
60
80
100
120
140


1371C Thunder Bay Ice Loads
TEST #2
RUN 01
Mar-20-84 @ 15:02:44
|< 1st >|< 2nd >|< 3rd >|
100
0
-100
-200
-300
Hex 1 aver
kN/m
100
0
-100
-200
-300
Hex 2 aver
kN/m
ANALOG DATA SATURATED
SEC 0
20
40
60
80
100
120
140

1371C Thunder Bay Ice Loads



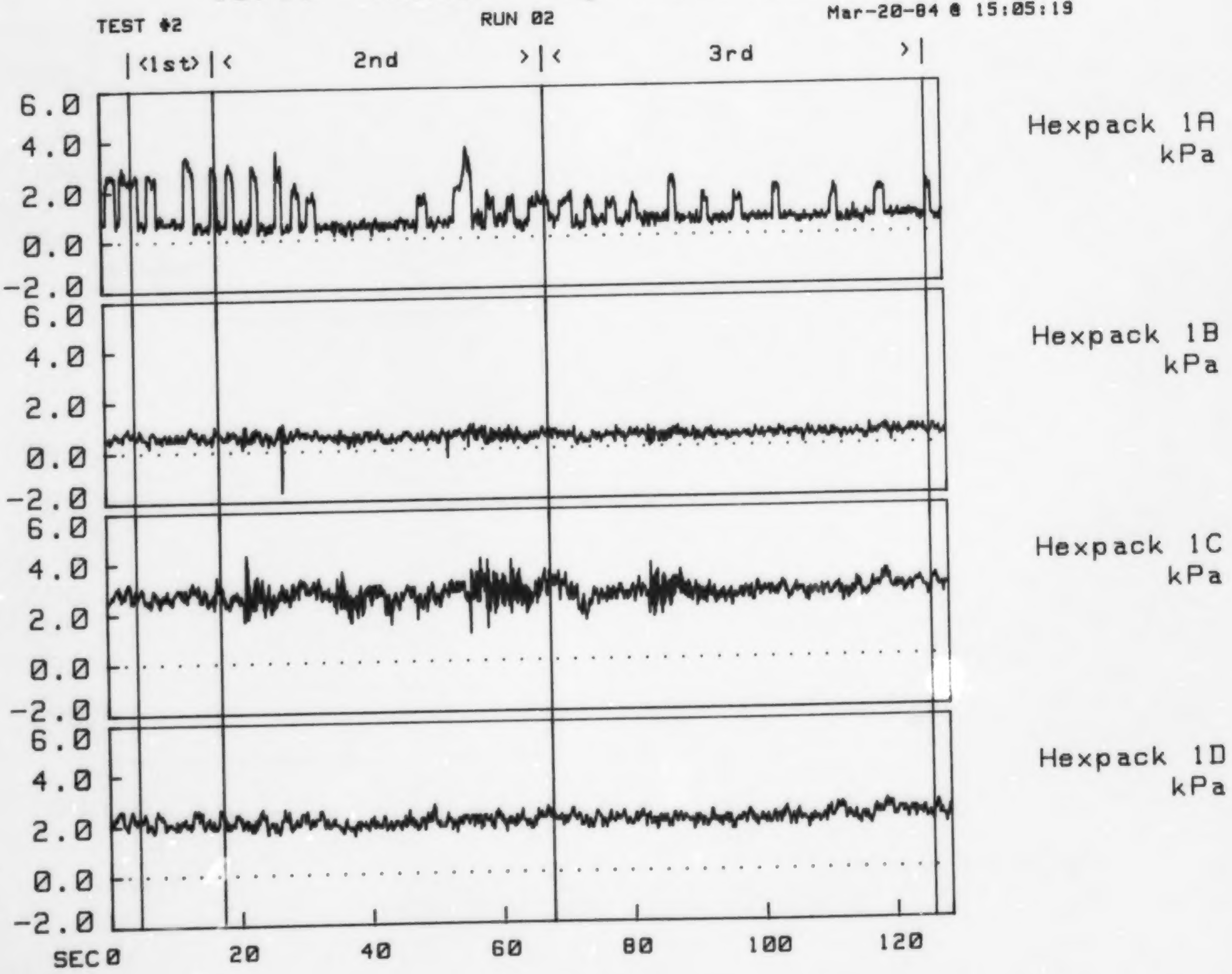
THUNDER BAY ICE LOAD SUMMARY

Test #: 2
Run #: 02
Date: Mar-20-84
Scan Begins at: 15:05:19
Duration of Scan: 130 SEC
Scan ends at: 15:07:29
Type of test: Alexander Henry with ACIB
Location of Ship: Hovering 20 m inside dock

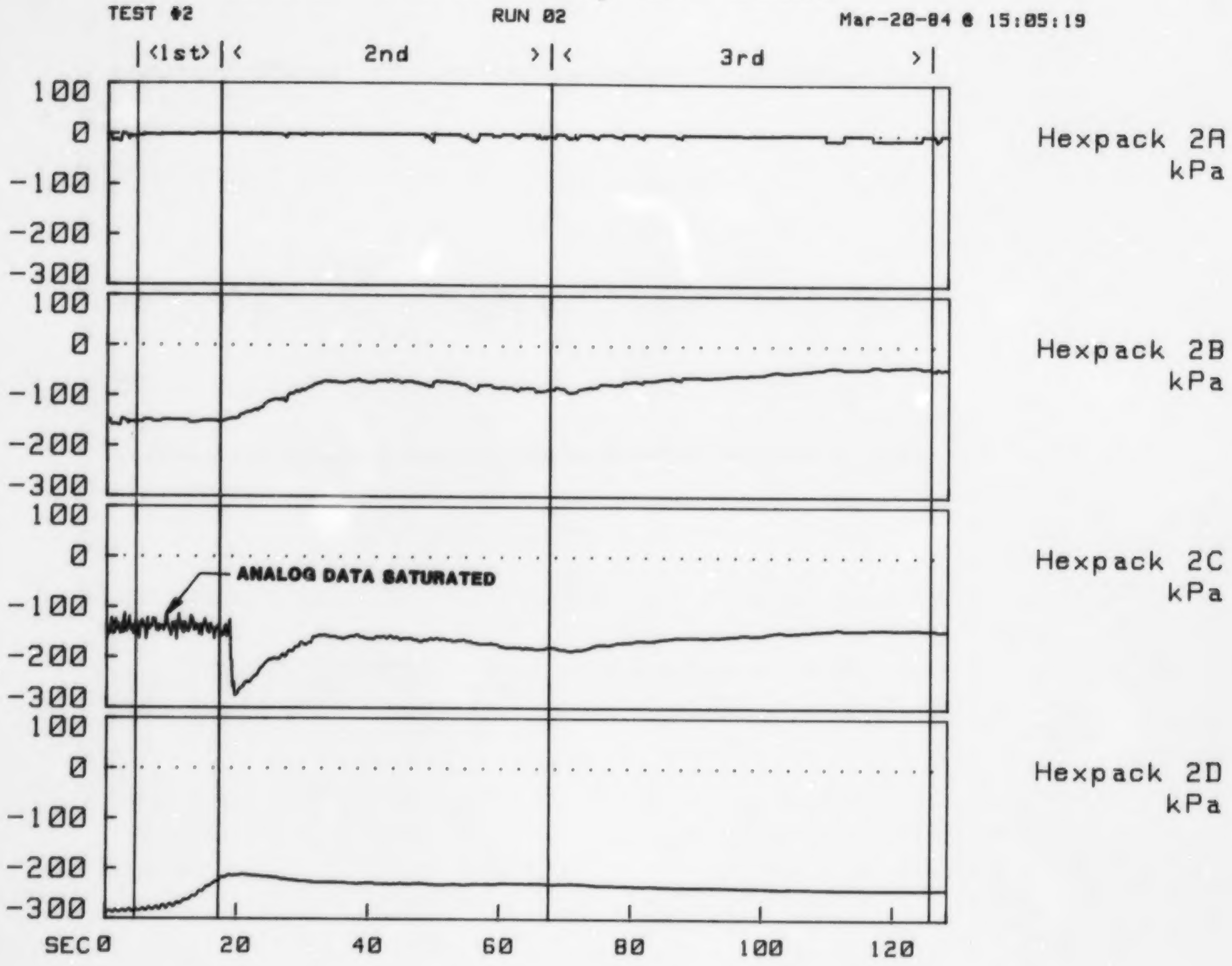
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1A	0.81	0.23	kPa
Hex 1B	1.07	-1.60	kPa
Hex 1C	4.28	1.11	kPa
Hex 1D	2.71	1.53	kPa
Hex 2A	2.01	-5.59	kPa
Hex 2B	-38.55	-154.58	kPa
Hex 2C	-125.78	-300.00	kPa
Hex 2D	-210.38	-284.51	kPa
Hex 3A	2.50	-1.79	kPa
Hex 3B	-59.95	-107.01	kPa
Hex 3C	-40.55	-350.00	kPa
Hex 3D	359.63	-199.88	kPa
Hex 4	20.78	-91.84	kPa
Accel.	0.00	0.00	g'S
Hex 1 aver	3.86	1.14	kN/m
Hex 2 aver	-141.67	-250.00*	kN/m
Hex 3 aver	50.00*	-112.10	kN/m
Hex 4 aver	41.55	-183.67	kN/m

Comments: Periodic communication throughout.
Hexpack 2C & 3C saturated the analog record.

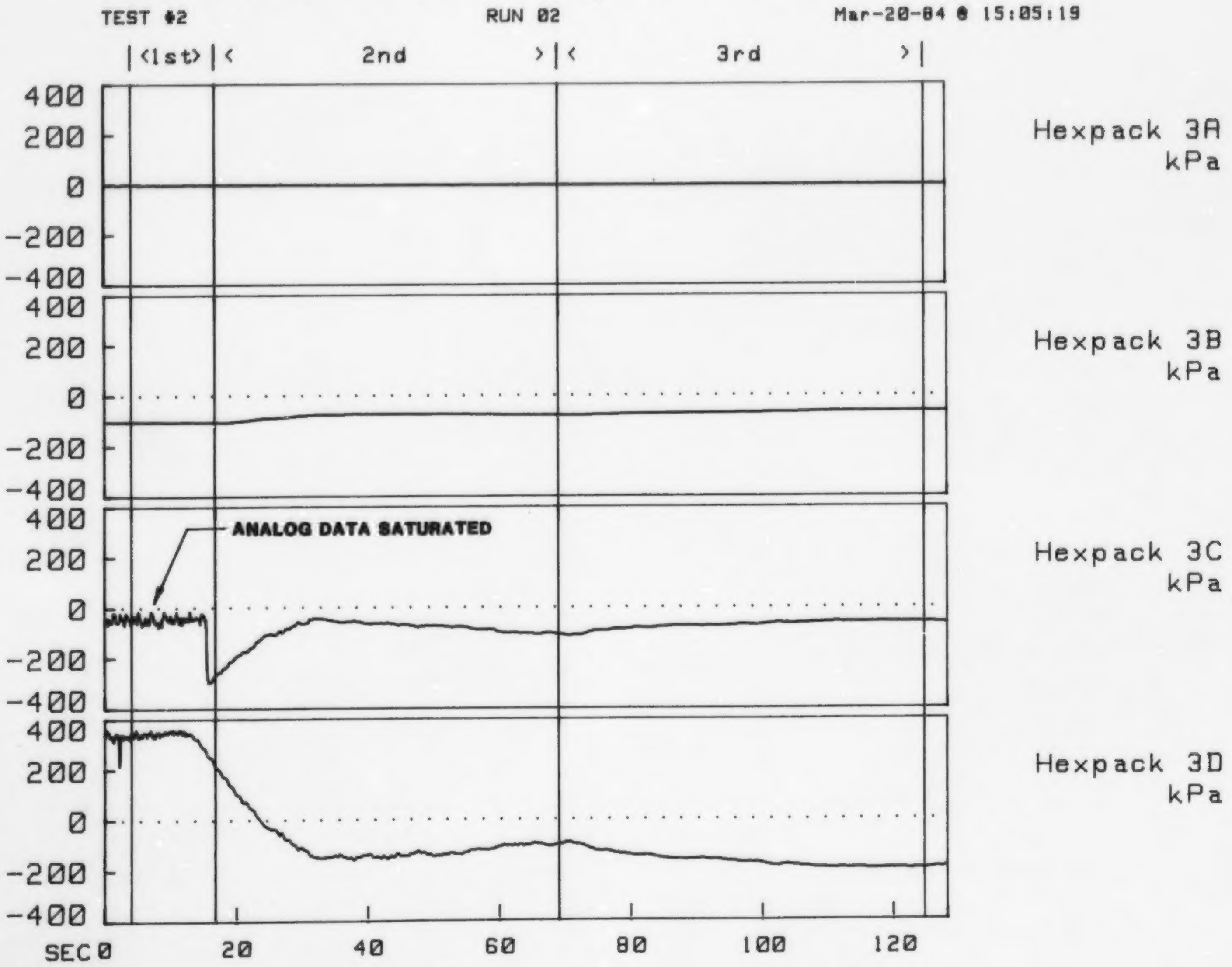
* Estimated


1371C Thunder Bay Ice Loads

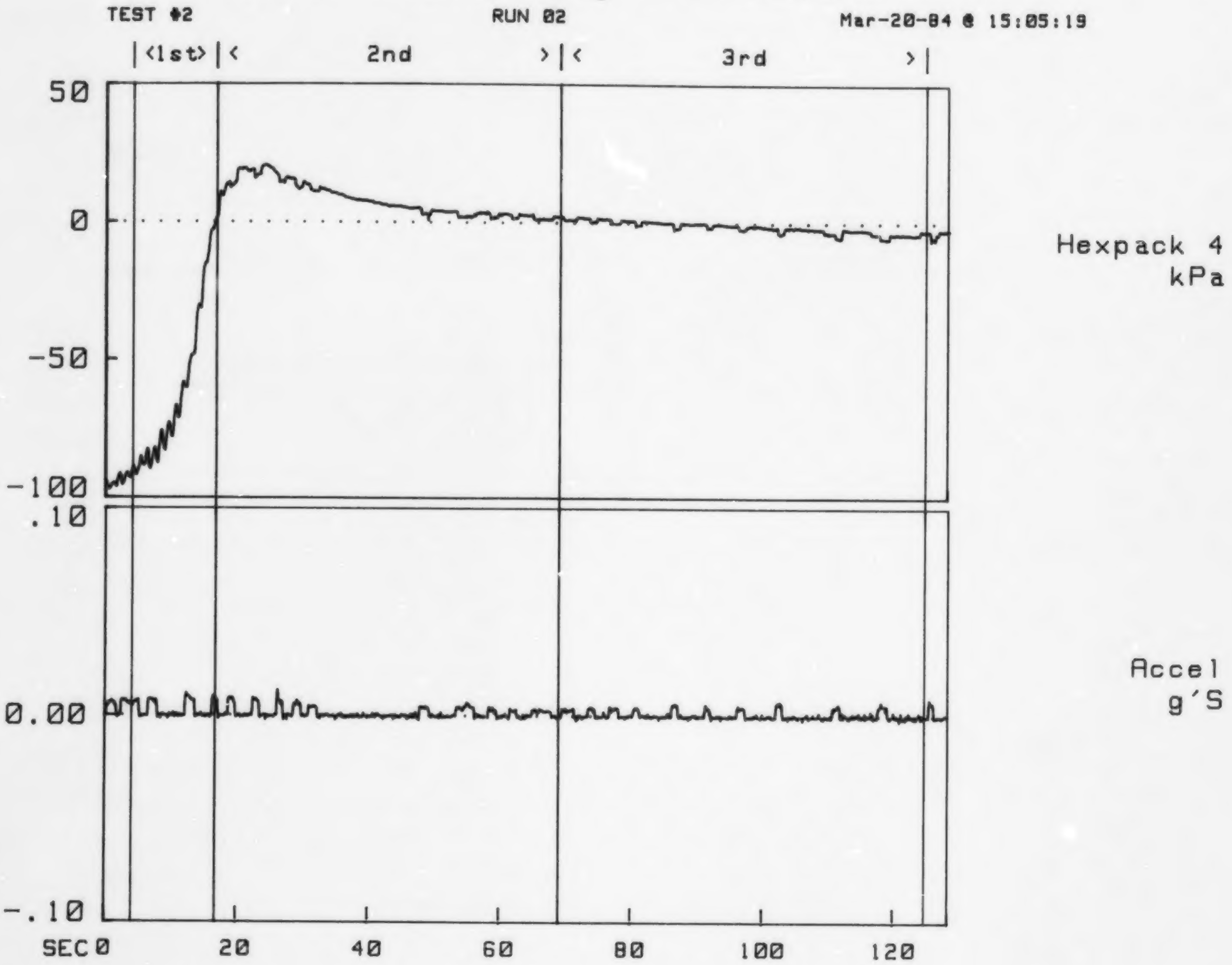
1371C Thunder Bay Ice Loads



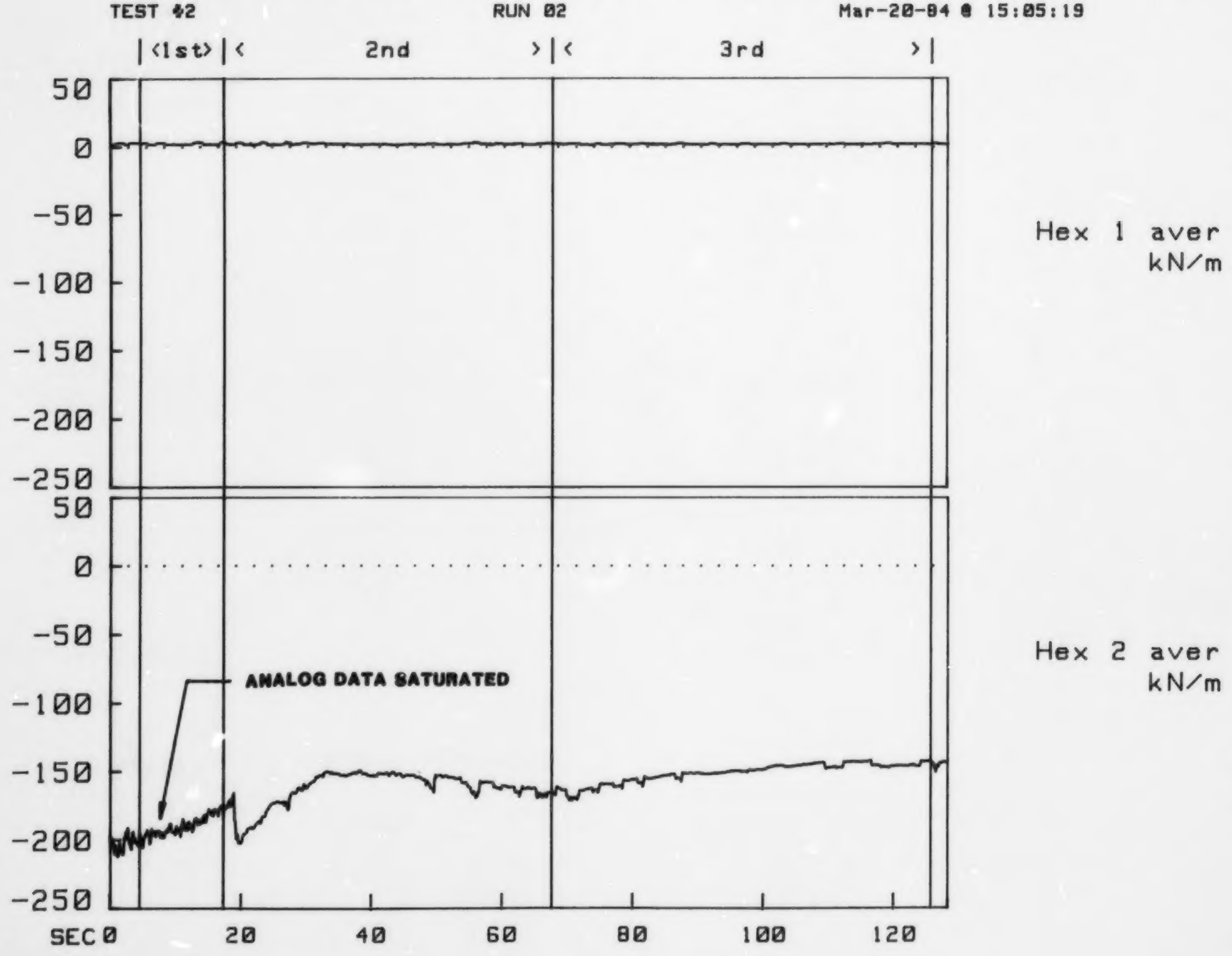
1371C Thunder Bay Ice Loads



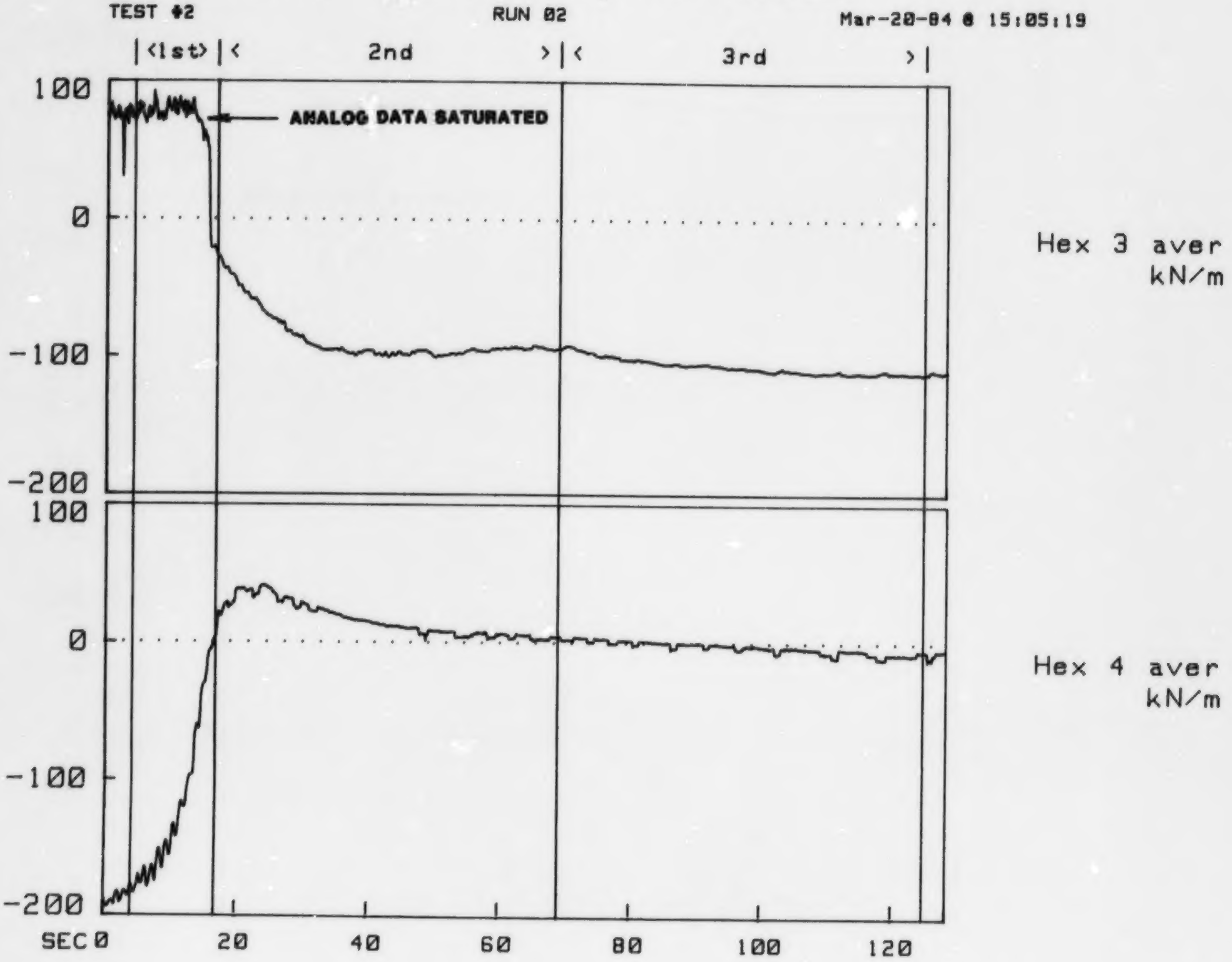
1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads



THUNDER BAY ICE LOAD TEST SUMMARY

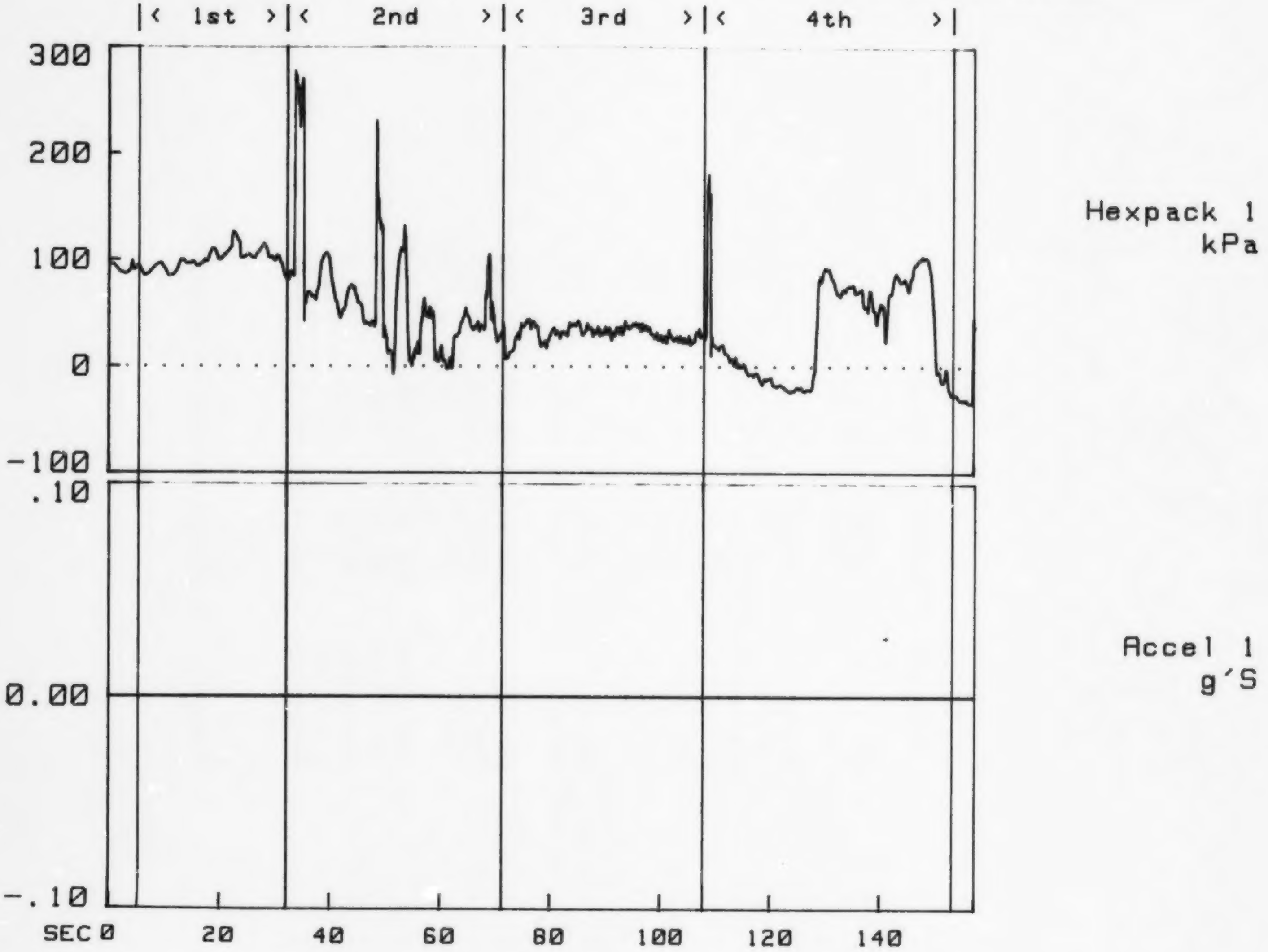
Test #:	3
Run #:	01
Date:	Mar-23-84
Scan Begins at:	10:46:29
Duration of Scan:	150 SEC
Scan ends at:	10:48:59
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 20 m inside dock Ends 45 m inside dock Breaking unbroken ice

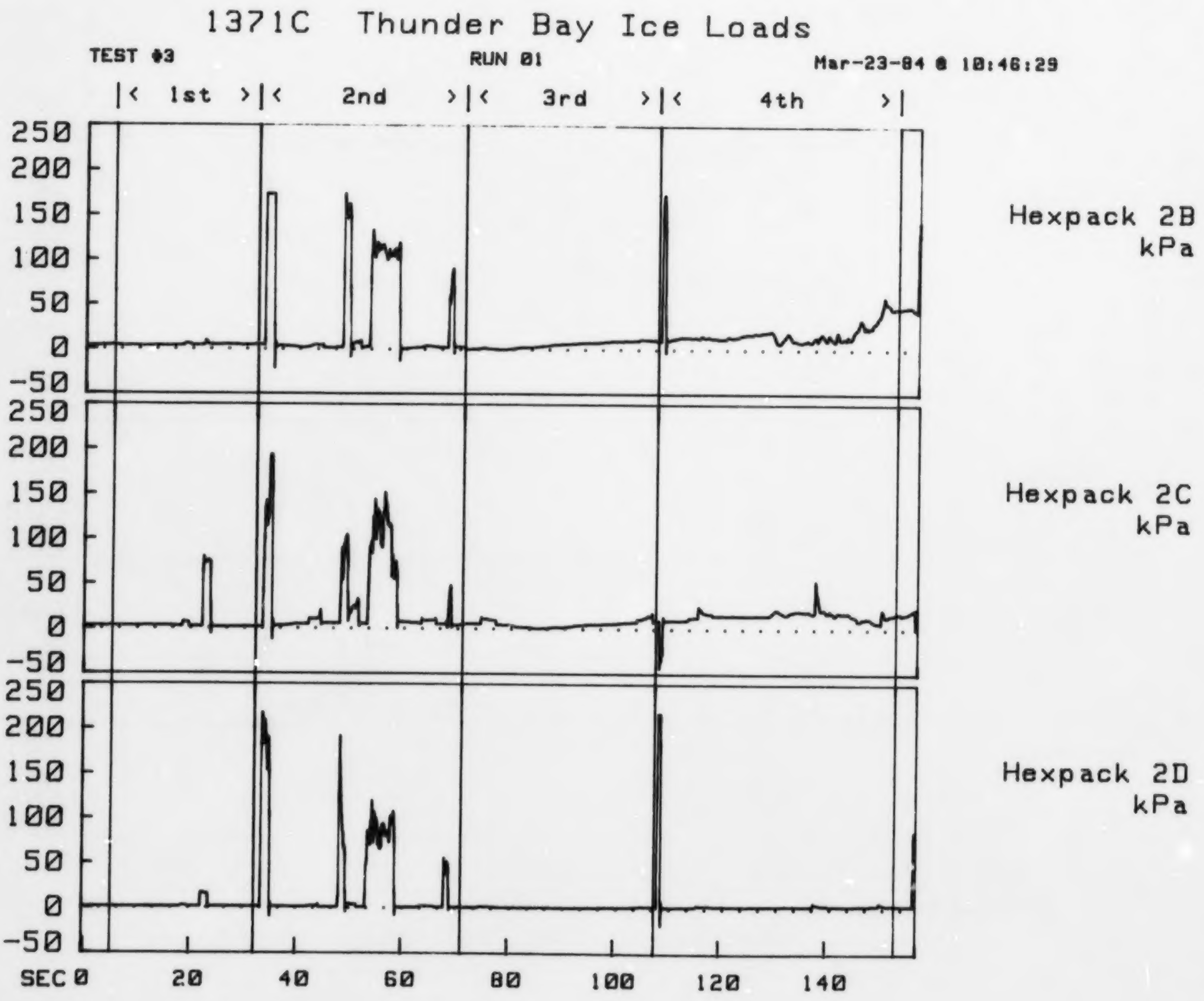
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	125.96	-26.57	kPa
Accel 1	0.00	0.00	g'S
Hex 2B	58.04	-0.36	kPa
Hex 2C	22.83	0.42	kPa
Hex 2D	6.37	0.98	kPa
Hex 3B	45.16	38.71	kPa
Hex 3C	-3.87	-11.61	kPa
Hex 3D	66.93	-15.48	kPa
Hex 4	15.90	-11.75	kPa
Accel 2	0.01	-0.01	g'S
Hex 5B	308.92	-0.99	kPa
Hex 5C	21.27	-2.71	kPa
Hex 5D	6.33	-1.55	kPa
Hex 1 aver	251.92	-53.14	kN/m
Hex 2 aver	25.81	0.25	kN/m
Hex 3 aver	52.21	8.60	kN/m
Hex 4 aver	23.85	-17.63	kN/m
Hex 5 aver	121.73	-0.67	kN/m

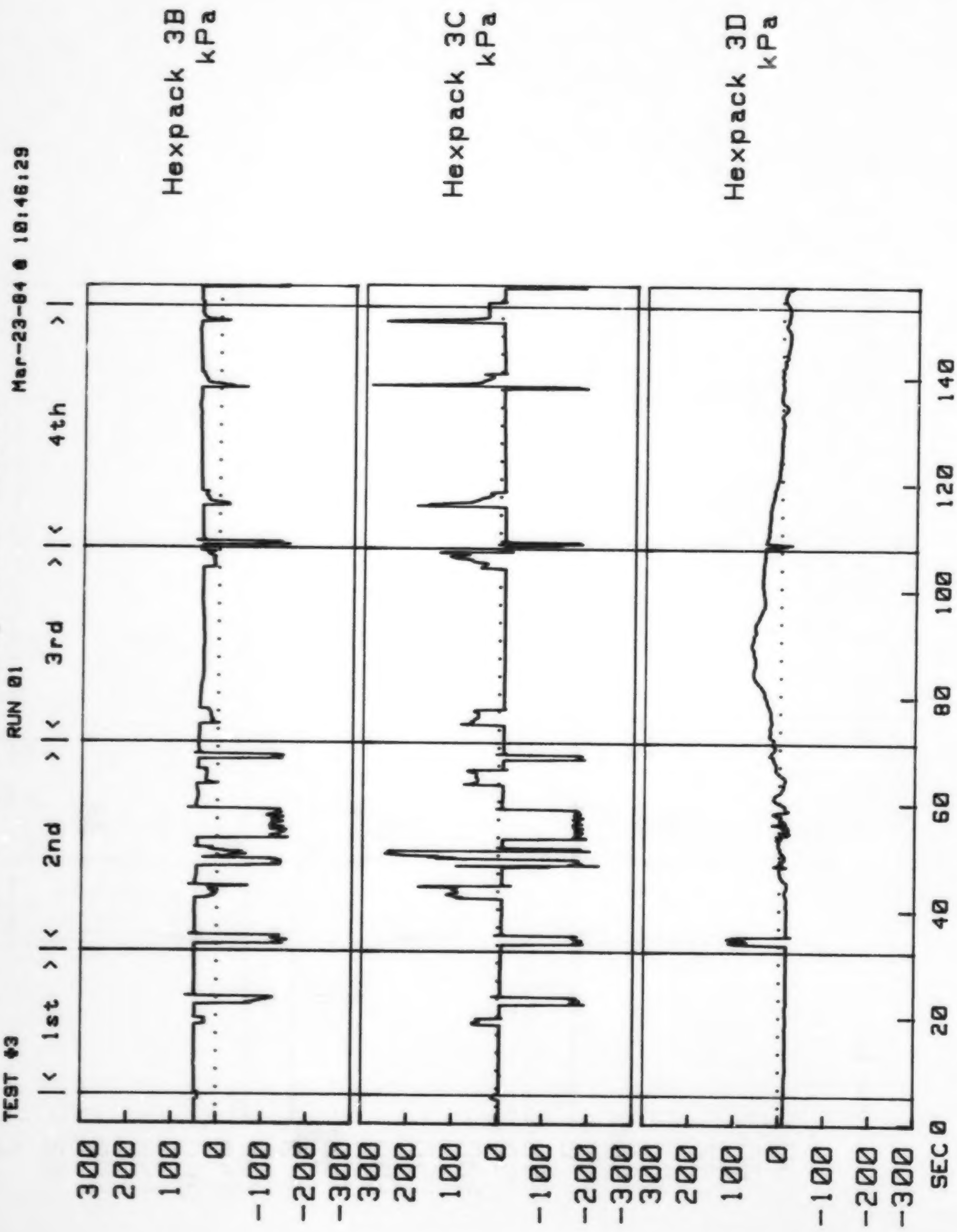
Comments: Periodic communication throughout.

1371C Thunder Bay Ice Loads

TEST #3 RUN 01 Mar-23-84 @ 10:46:29



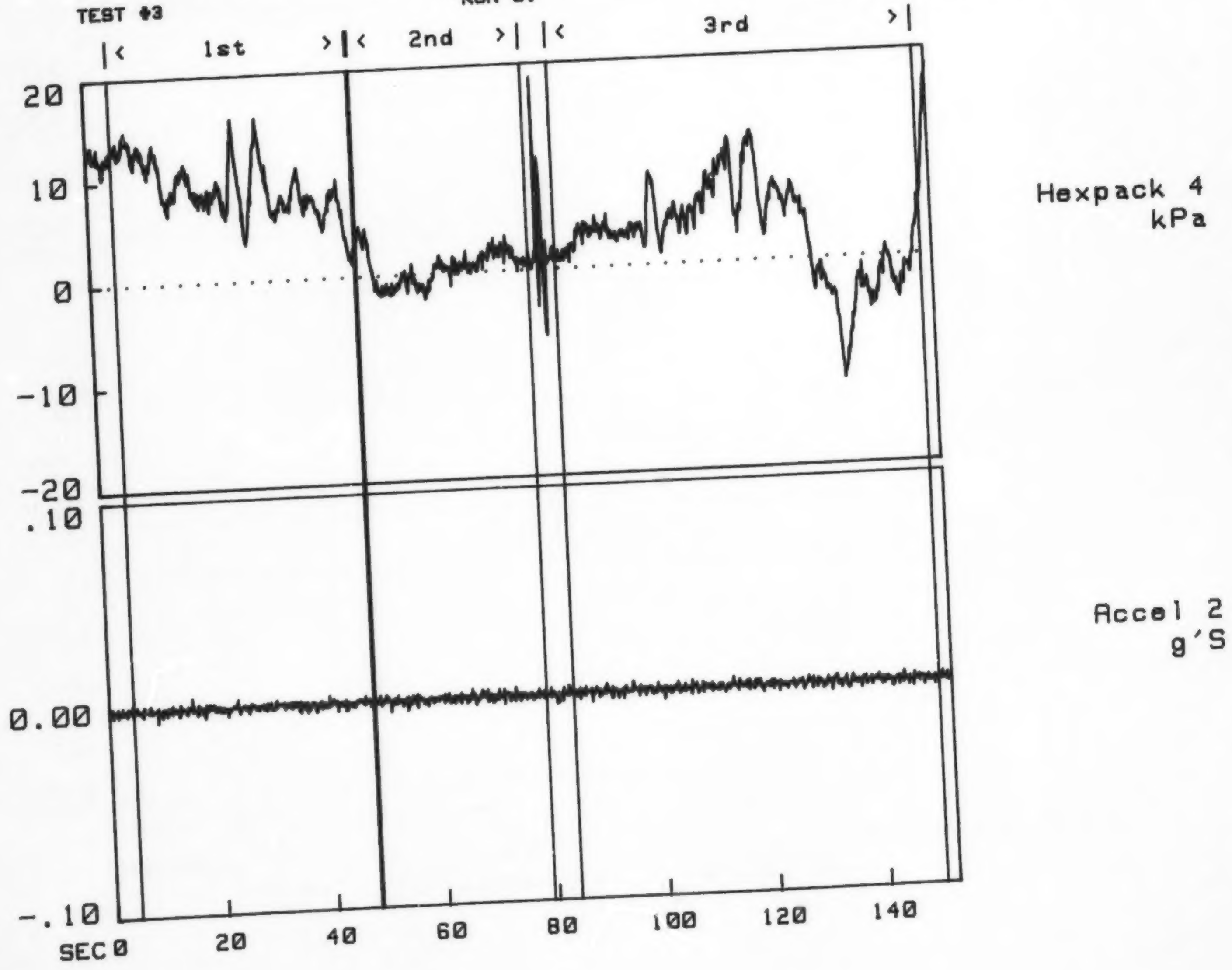

1371C Thunder Bay Ice Loads
TEST #3
RUN 01
Mar-23-84 @ 10:46:29
|< 1st >|< 2nd >|< 3rd >|< 4th >|
Hexpack 2B
kPa
Hexpack 2C
kPa
Hexpack 2D
kPa
250
200
150
100
50
0
-50
SEC 0
20
40
60
80
100
120
140



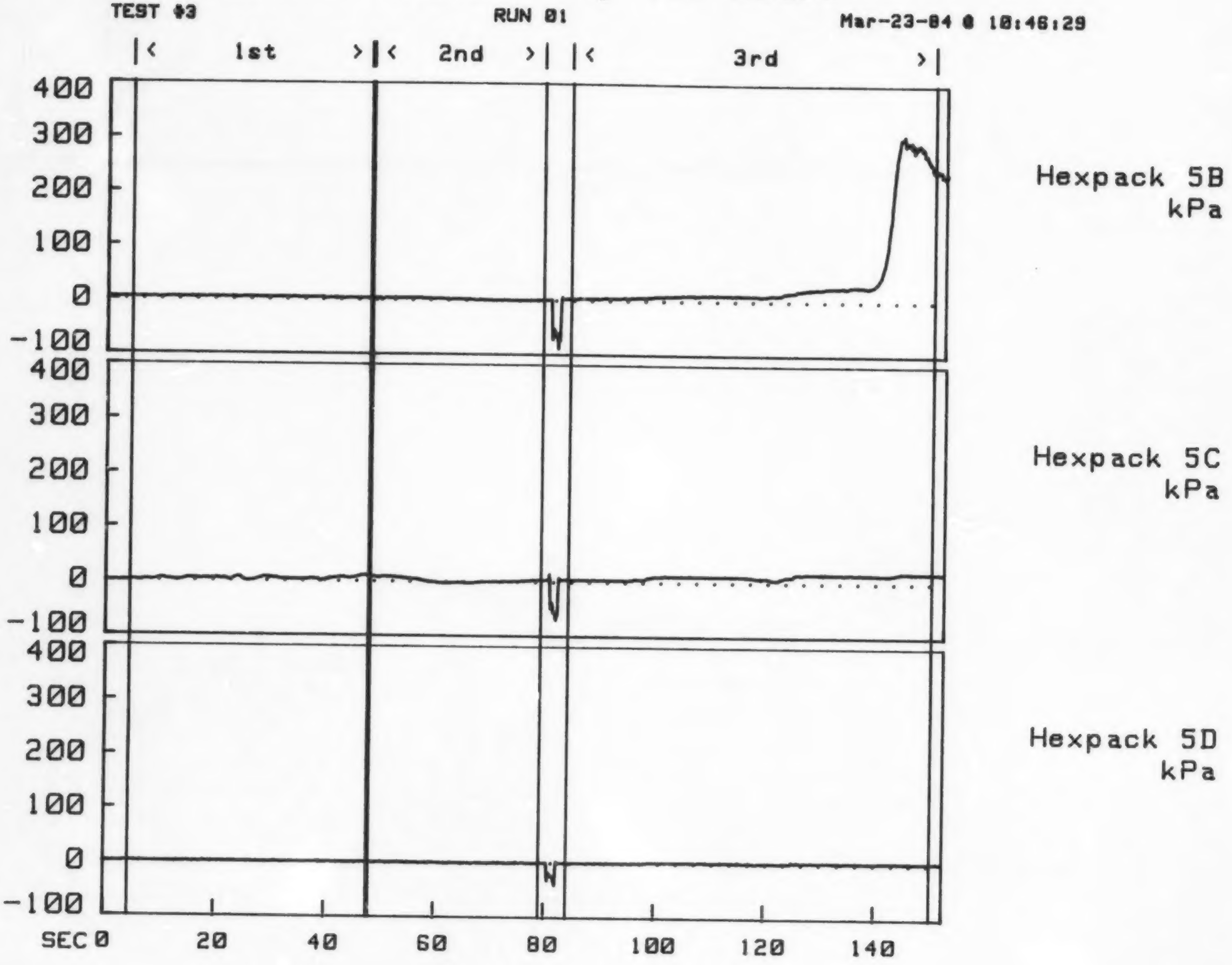
1371C Thunder Bay Ice Loads

1371C Thunder Bay Ice Loads

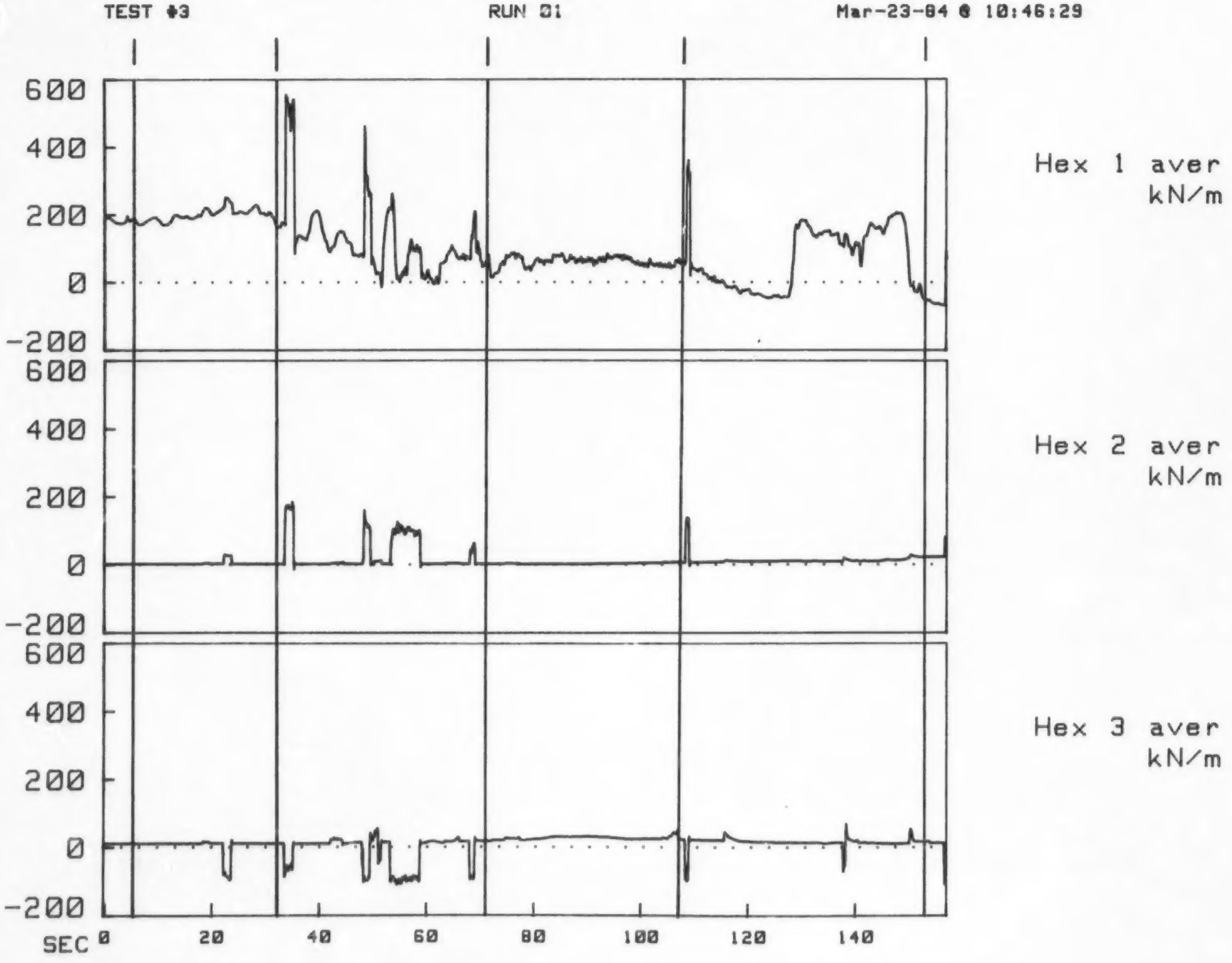
Mar-23-84 @ 10:46:29



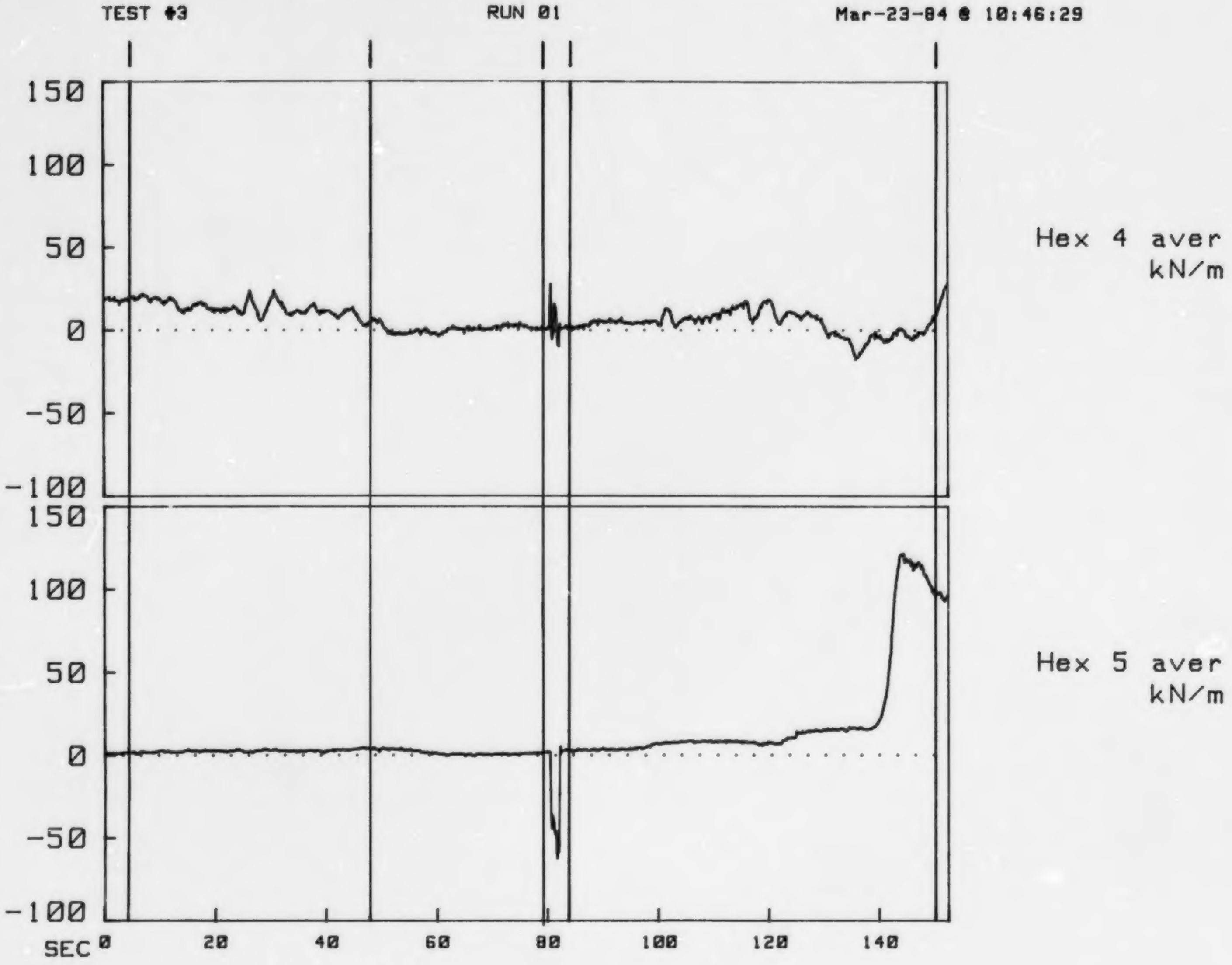
1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads



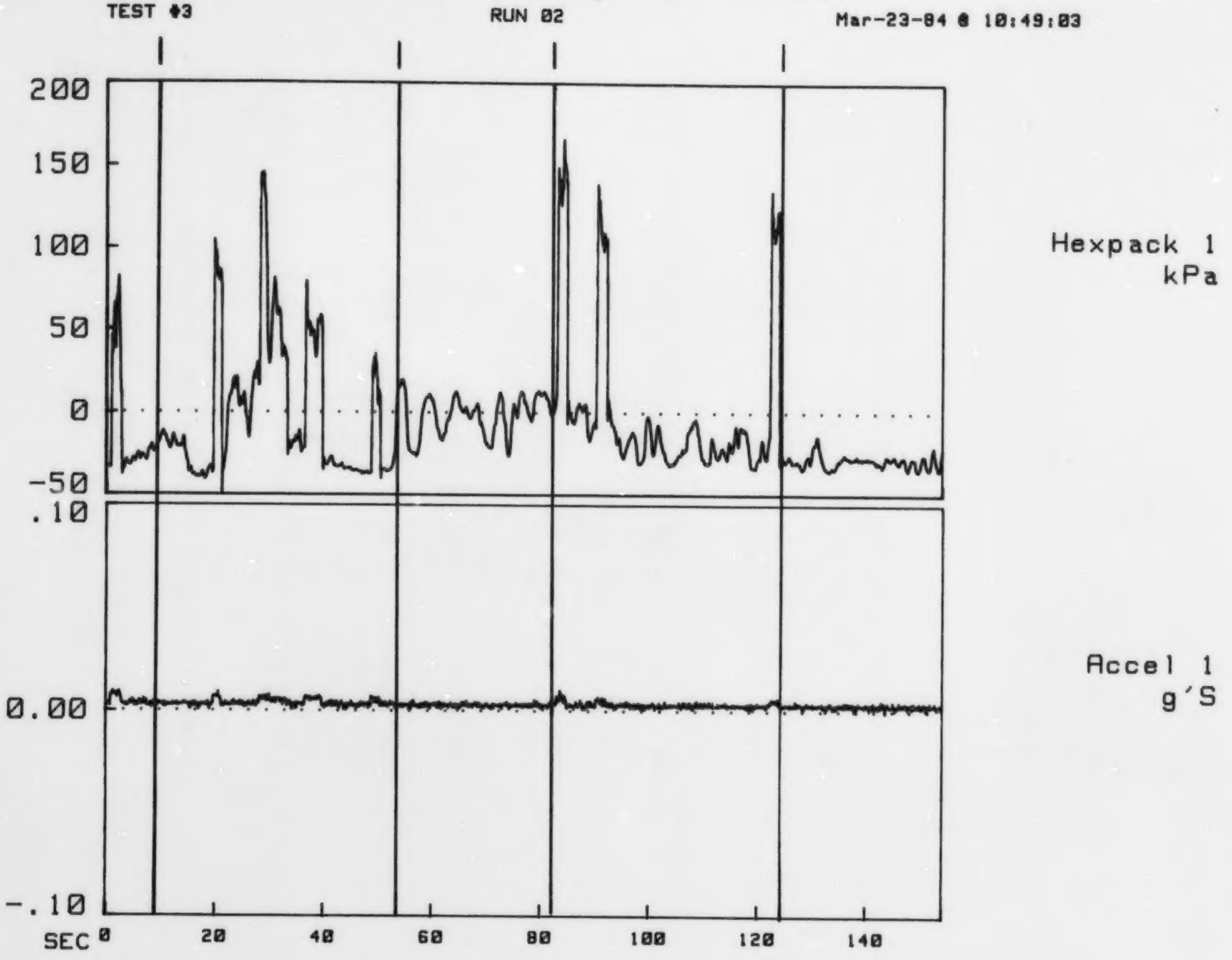
THUNDER BAY ICE LOAD TEST SUMMARY

Test #:	3
Run #:	02
Date:	Mar-23-84
Scan Begins at:	10:49:03
Duration of Scan:	150 sec
Scan ends at:	10:51:33
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 45 m inside dock Ends 70 m inside dock Breaking unbroken ice

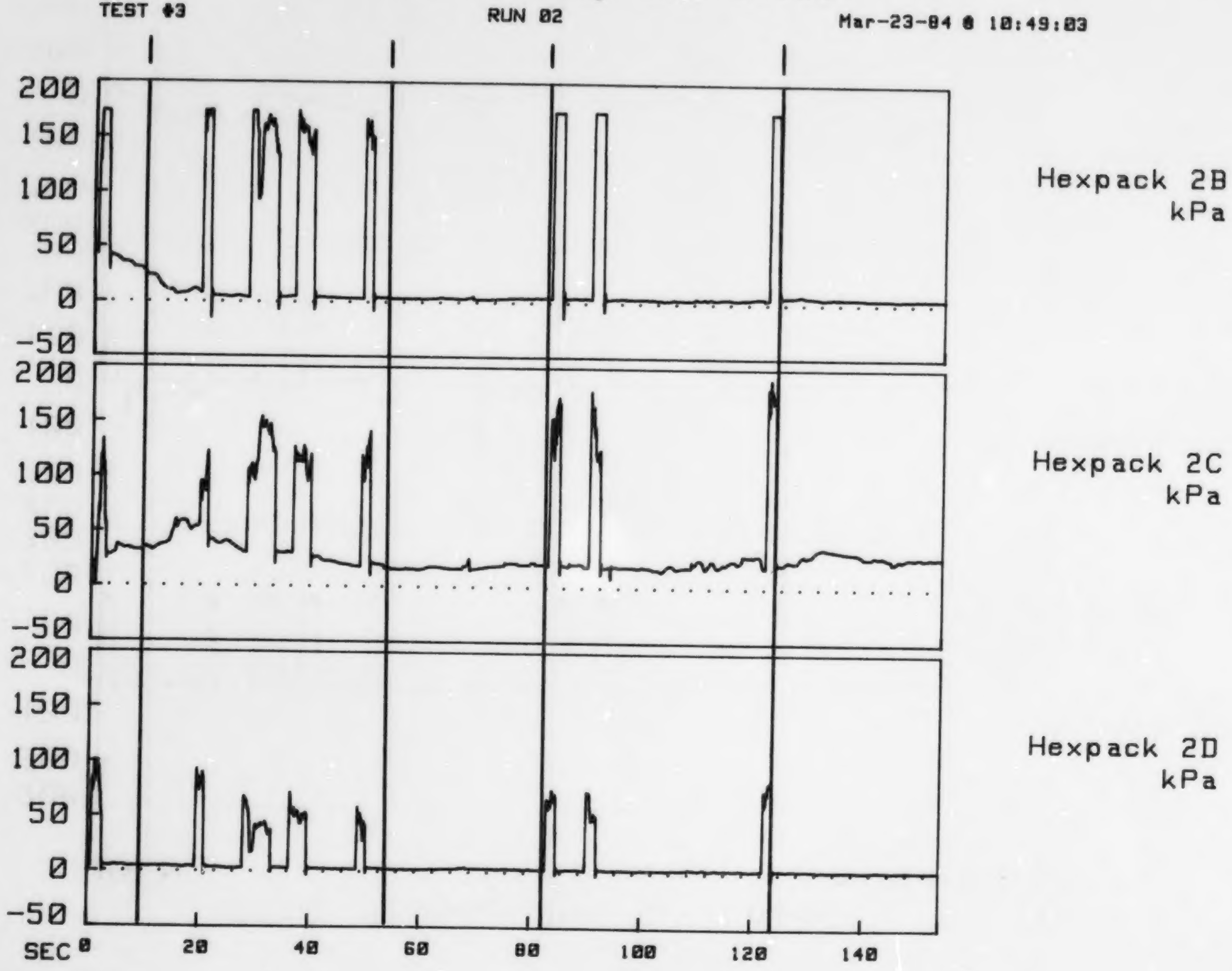
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	19.80	-42.55	kPa
Accel 1	0.01	0.00	g'S
Hex 2B	45.70	4.30	kPa
Hex 2C	59.14	15.05	kPa
Hex 2D	4.84	2.15	kPa
Hex 3B	42.58	19.35	kPa
Hex 3C	3.87	-11.61	kPa
Hex 3D	96.77	-23.07	kPa
Hex 4	20.48	-26.07	kPa
Accel 2	0.00	-0.01	g'S
Hex 5B	370.15	44.10	kPa
Hex 5C	20.40	4.94	kPa
Hex 5D	6.77	0.64	kPa
Hex 1 aver	42.58	-80.00	kN/m
Hex 2 aver	24.52	11.21	kN/m
Hex 3 aver	36.13	10.32	kN/m
Hex 4 aver	23.10	-39.11	kN/m
Hex 5 aver	143.85	21.39	kN/m

Comments: Periodic communication throughout.

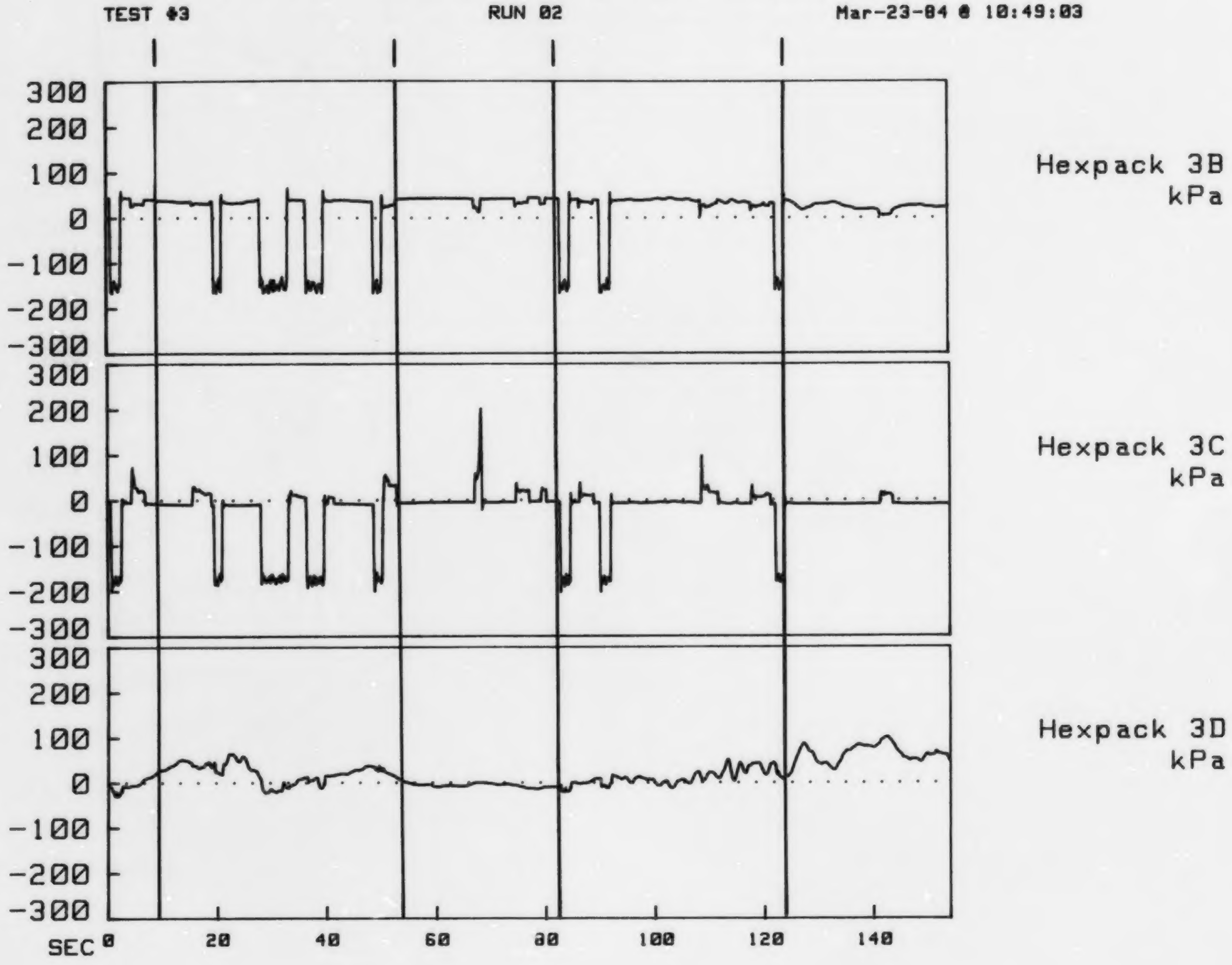
1371C Thunder Bay Ice Loads

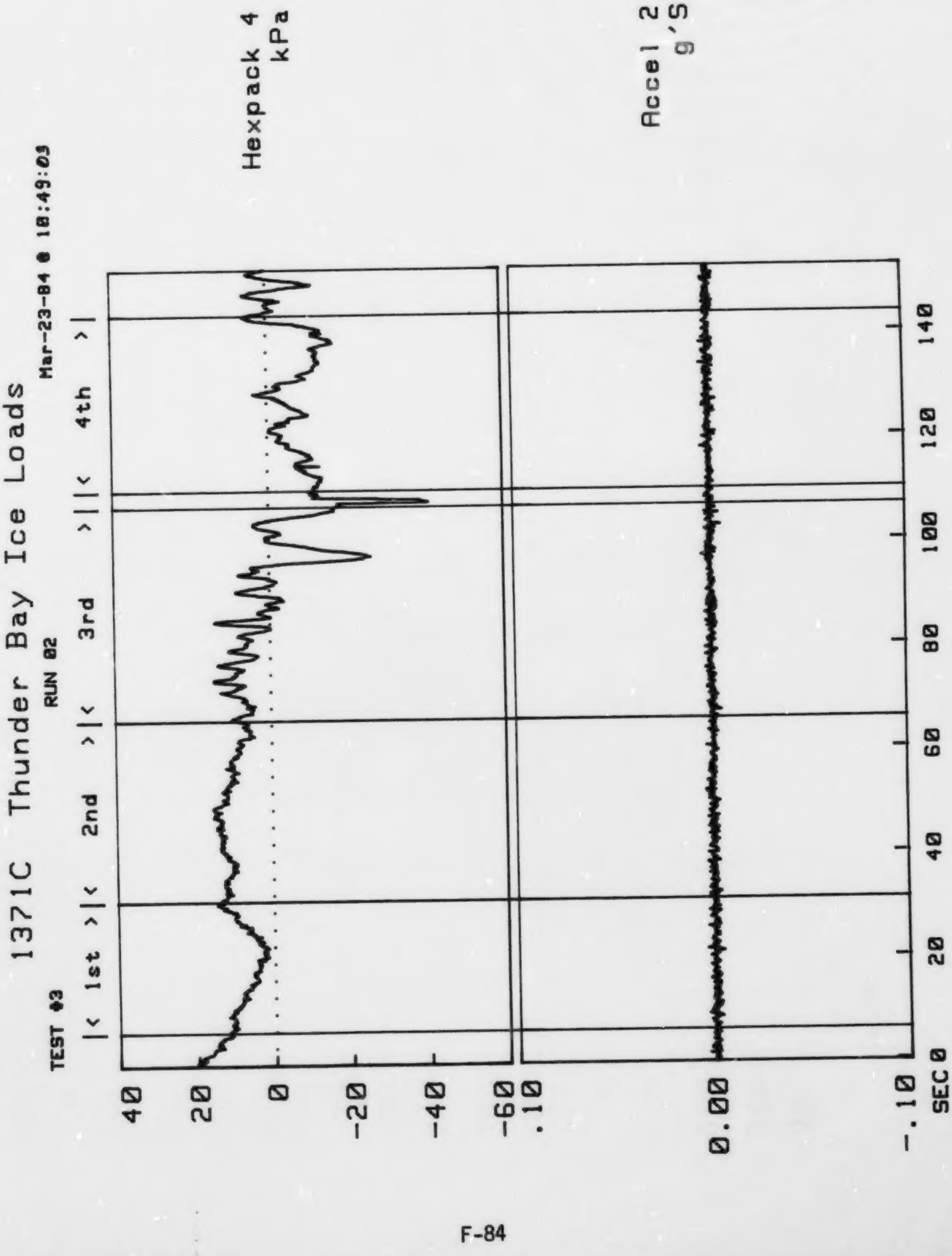


1371C Thunder Bay Ice Loads

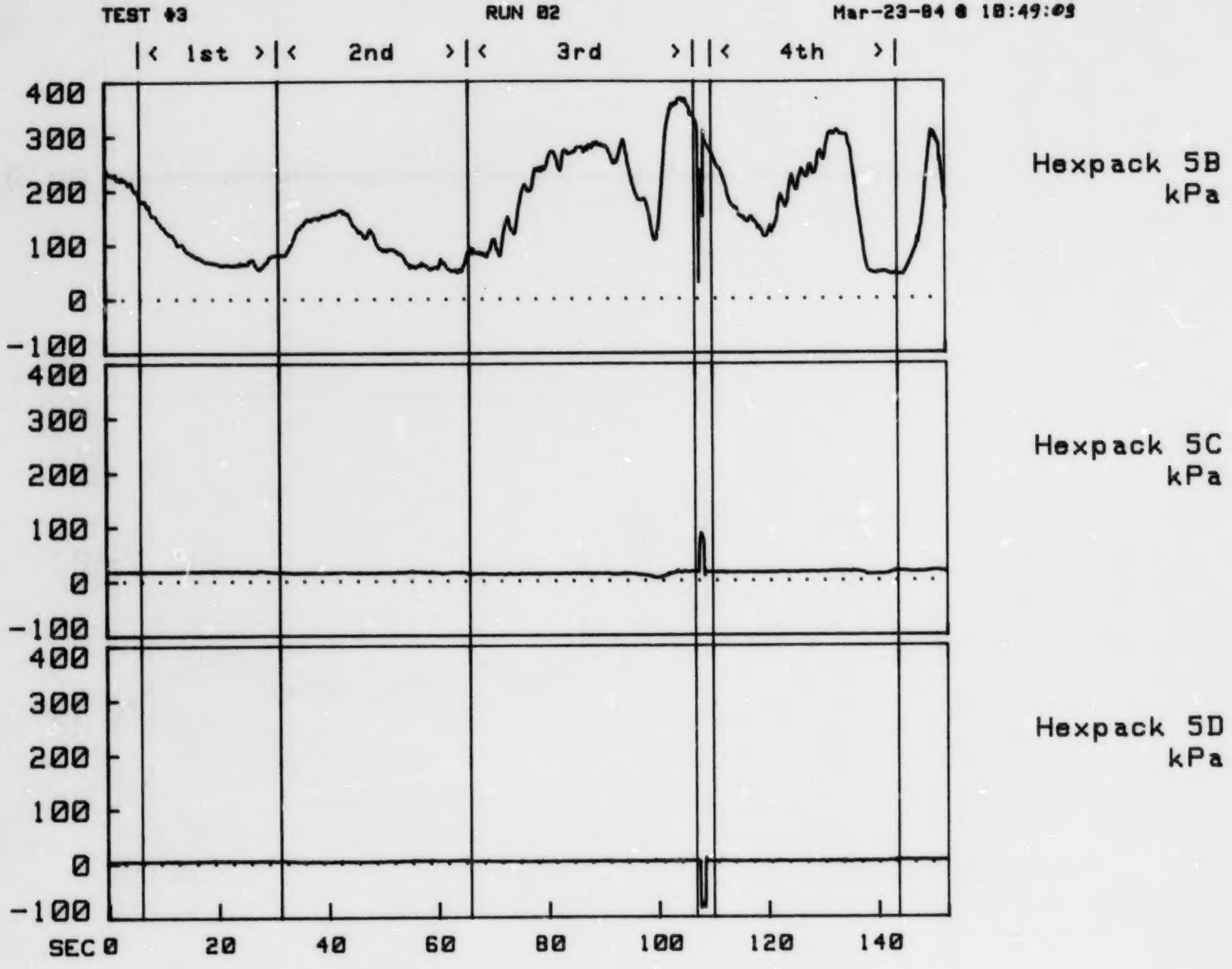


1371C Thunder Bay Ice Loads



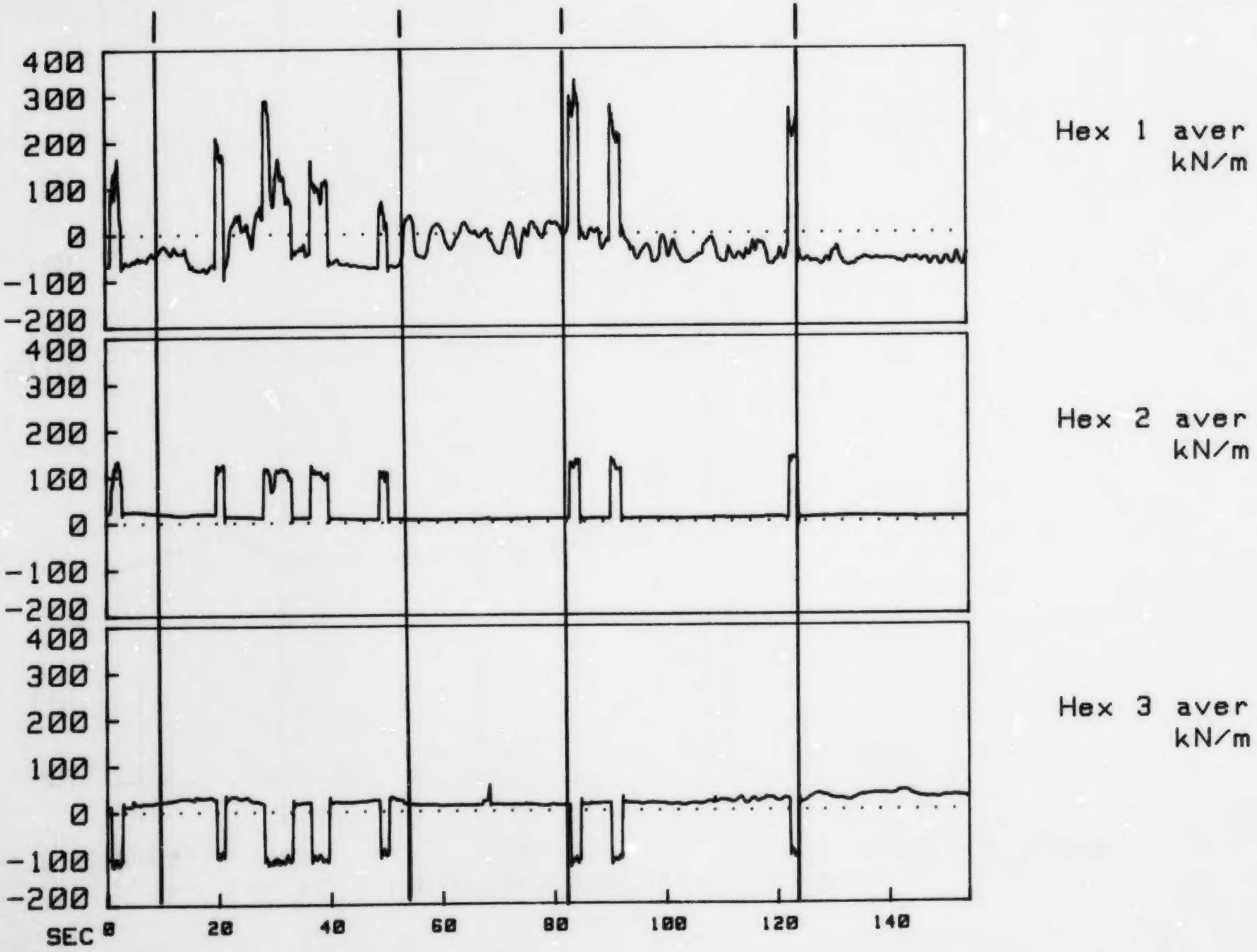

1371C Thunder Bay Ice Loads
TEST 03
RUN 02
Mar-23-84 @ 10:49:03
|< 1st >|< 2nd >|< 3rd >||< 4th >|
Hexpack 4
kPa
40
20
0
-20
-40
-60
Accel 2
g'S
.10
0.00
-.10
SEC 0
20
40
60
80
100
120
140

1371C Thunder Bay Ice Loads

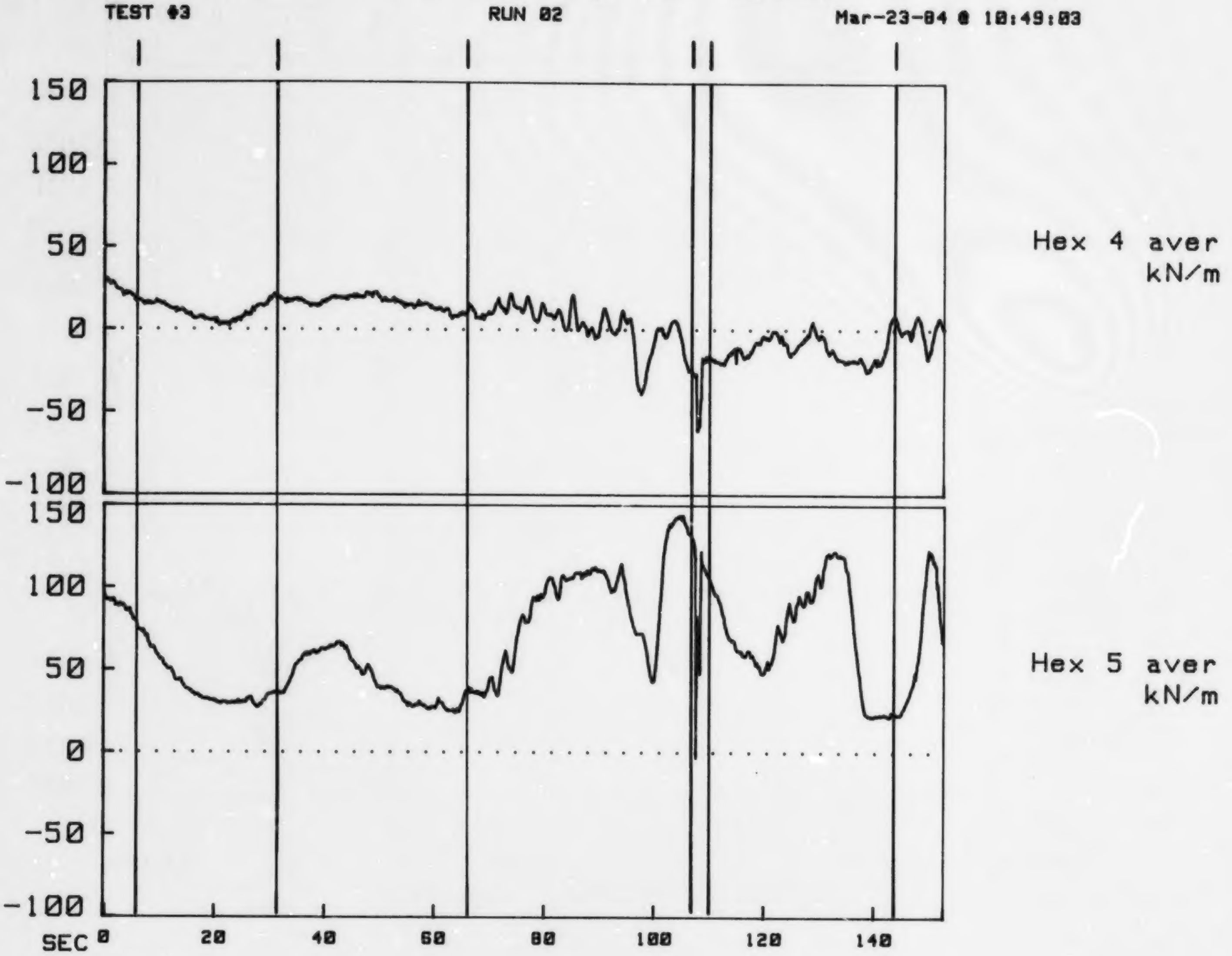


1371C Thunder Bay Ice Loads

TEST #3 RUN 02 Mar-23-84 @ 10:49:03



1371C Thunder Bay Ice Loads



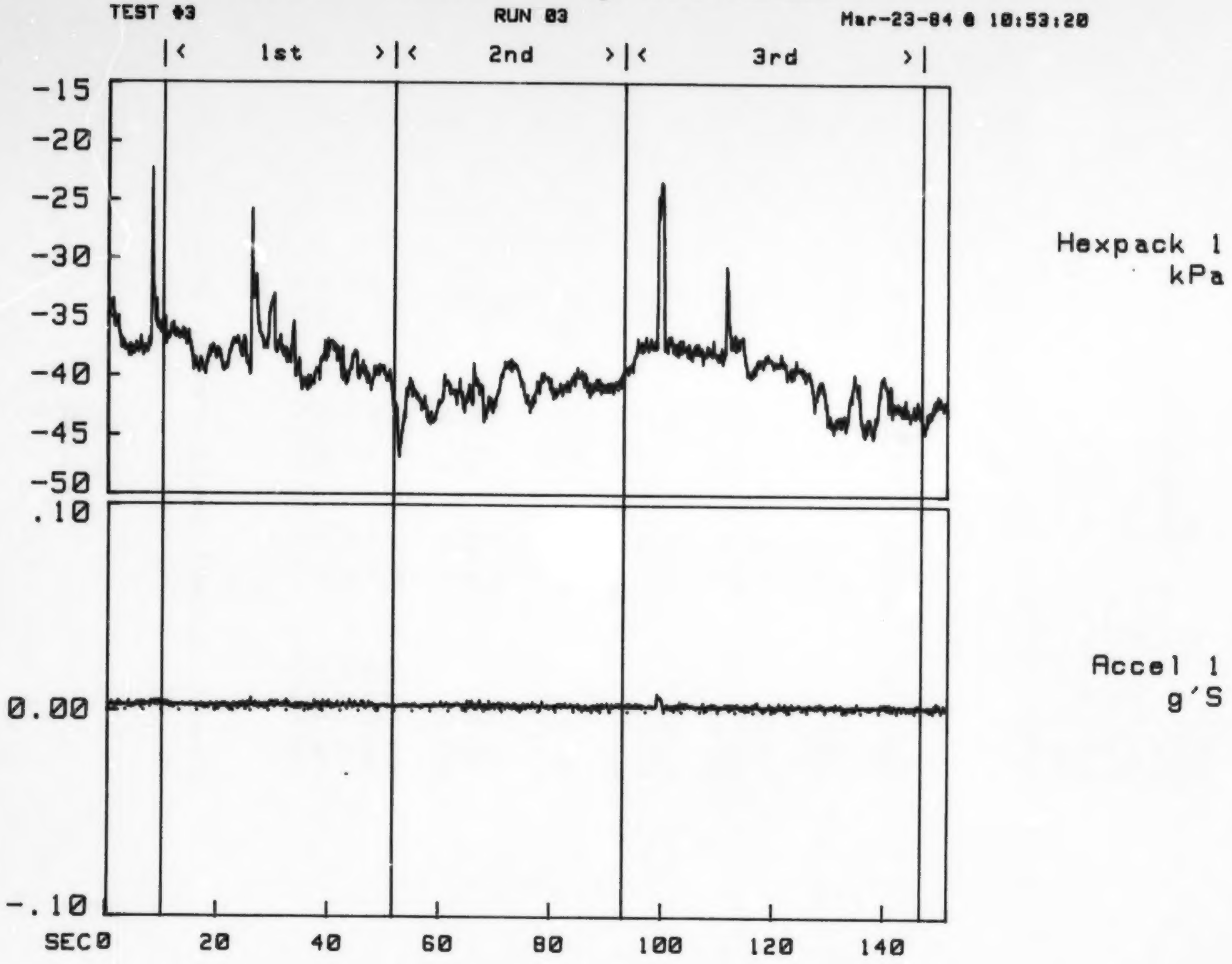
THUNDER BAY ICE LOAD TEST SUMMARY

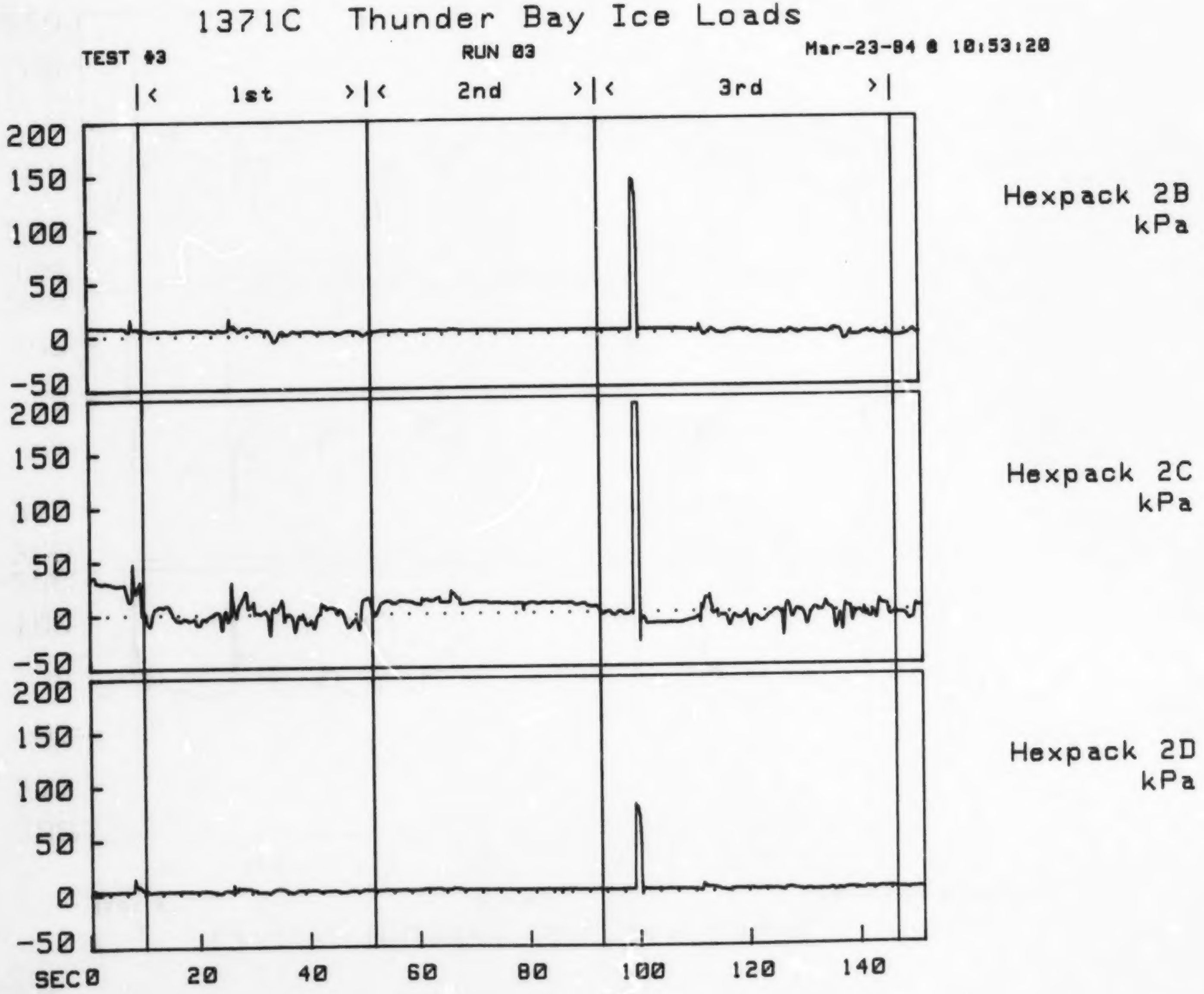
Test #:	3
Run #:	03
Date:	Mar-23-84
Scan Begins at:	10:53:20
Duration of Scan:	150 sec
Scan ends at:	10:55:50
Type of test:	Alexander Henry with ACIB
Location of Ship:	Starts 100 m inside dock Ends 145 m inside dock Breaking unbroken ice

TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	-33.12	-46.77	kPa
Accel 1	0.01	0.00	g'S
Hex 2B	5.34	-7.87	kPa
Hex 2C	29.73	-26.68	kPa
Hex 2D	7.77	-2.25	kPa
Hex 3B	42.77	0.00	kPa
Hex 3C	-5.38	-10.75	kPa
Hex 3D	221.36	-6.26	kPa
Hex 4	23.06	-44.06	kPa
Accel 2	0.00	0.00	g'S
Hex 5B	290.80	-1.38	kPa
Hex 5C	28.05	-2.36	kPa
Hex 5D	6.77	-2.86	kPa
Hex 1 aver	-70.97	-93.55	kN/m
Hex 2 aver	8.99	-2.66	kN/m
Hex 3 aver	85.10	11.46	kN/m
Hex 4 aver	30.60	-66.09	kN/m
Hex 5 aver	113.11	-1.55	kN/m

Comments: Periodic communication throughout.

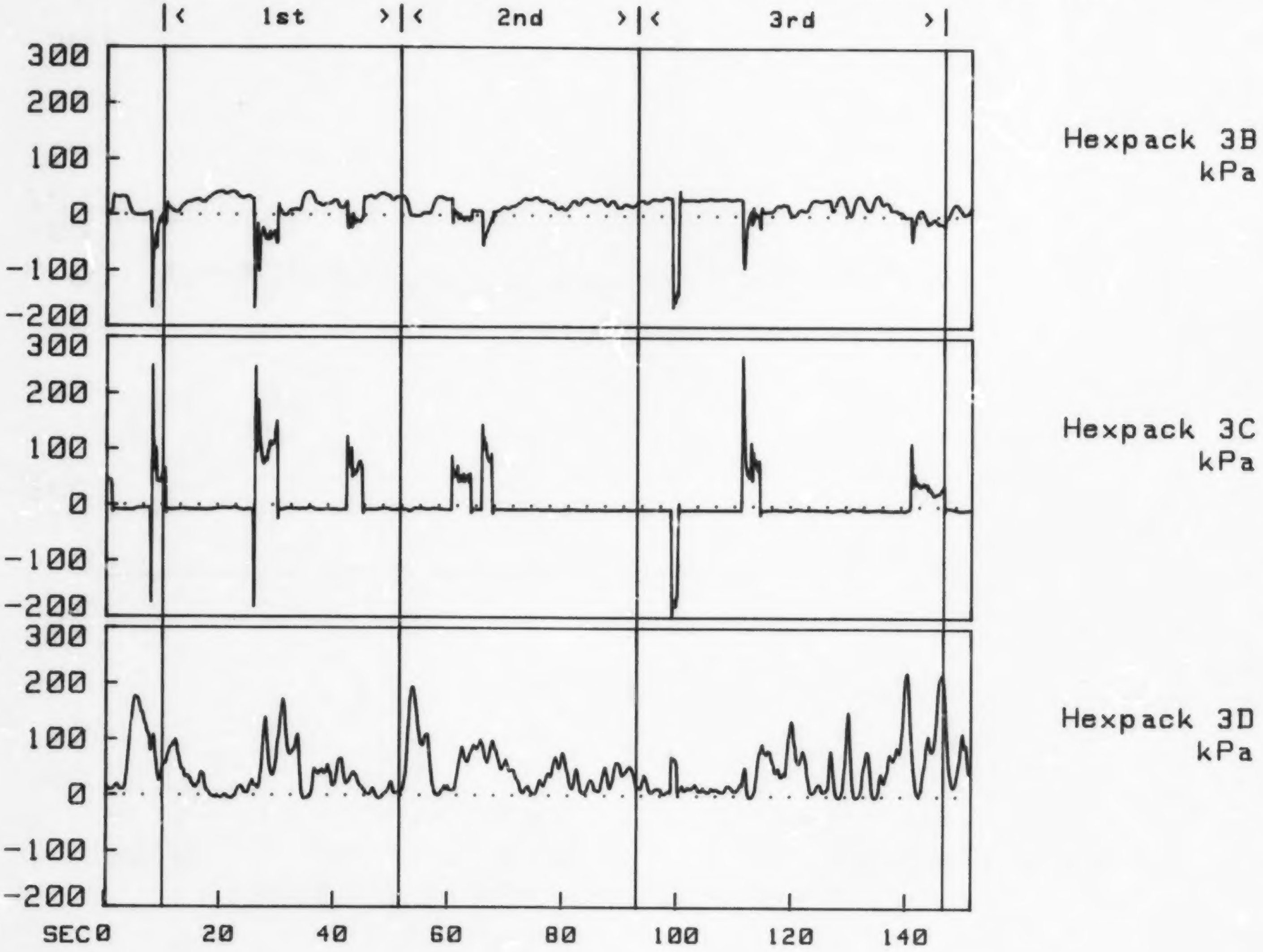
1371C Thunder Bay Ice Loads

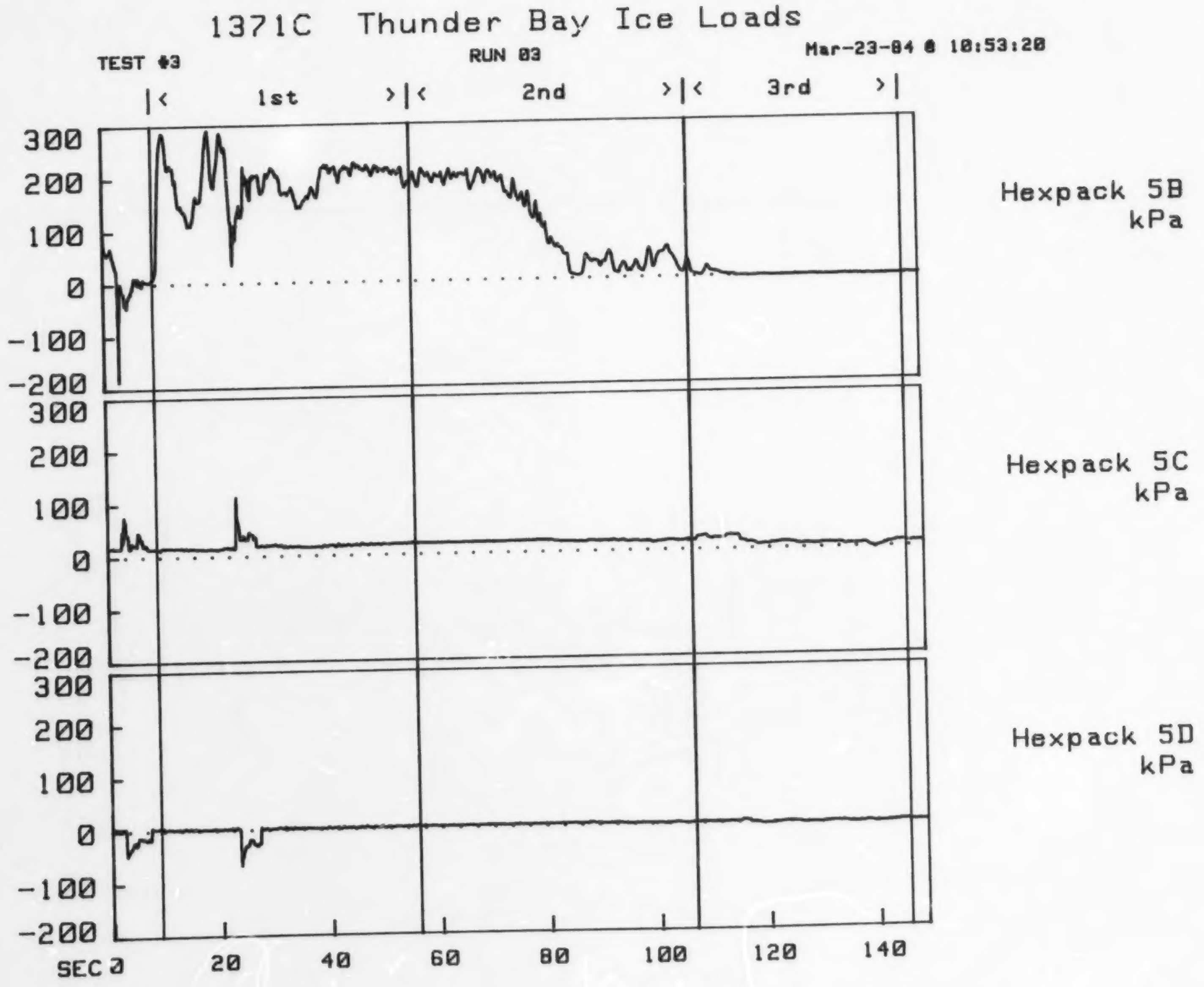


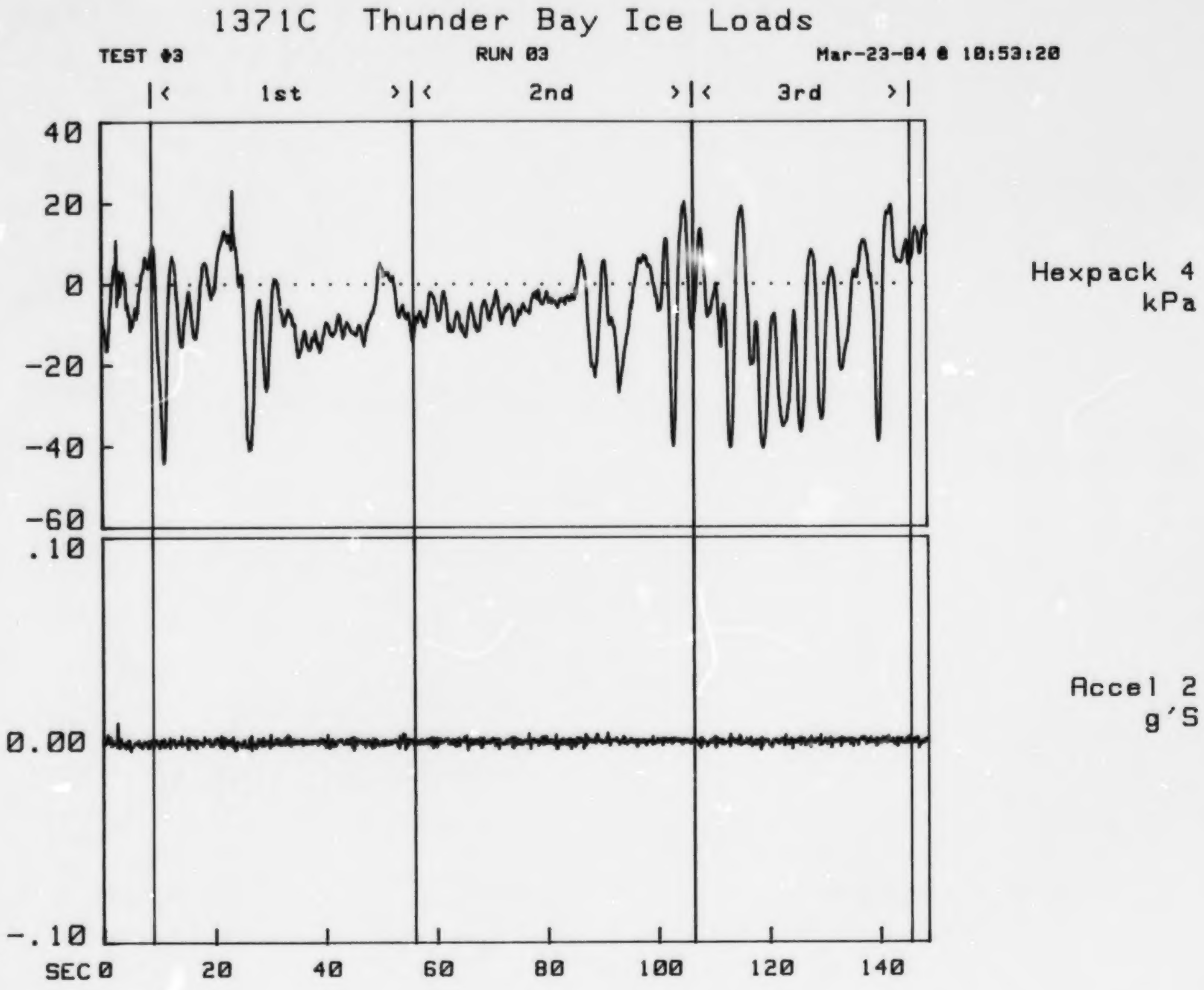

1371C Thunder Bay Ice Loads
TEST #3
RUN 03
Mar-23-84 @ 10:53:20
|< 1st >|< 2nd >|< 3rd >|
200
150
100
50
0
-50
Hexpack 2B
kPa
Hexpack 2C
kPa
Hexpack 2D
kPa
SEC 0
20
40
60
80
100
120
140

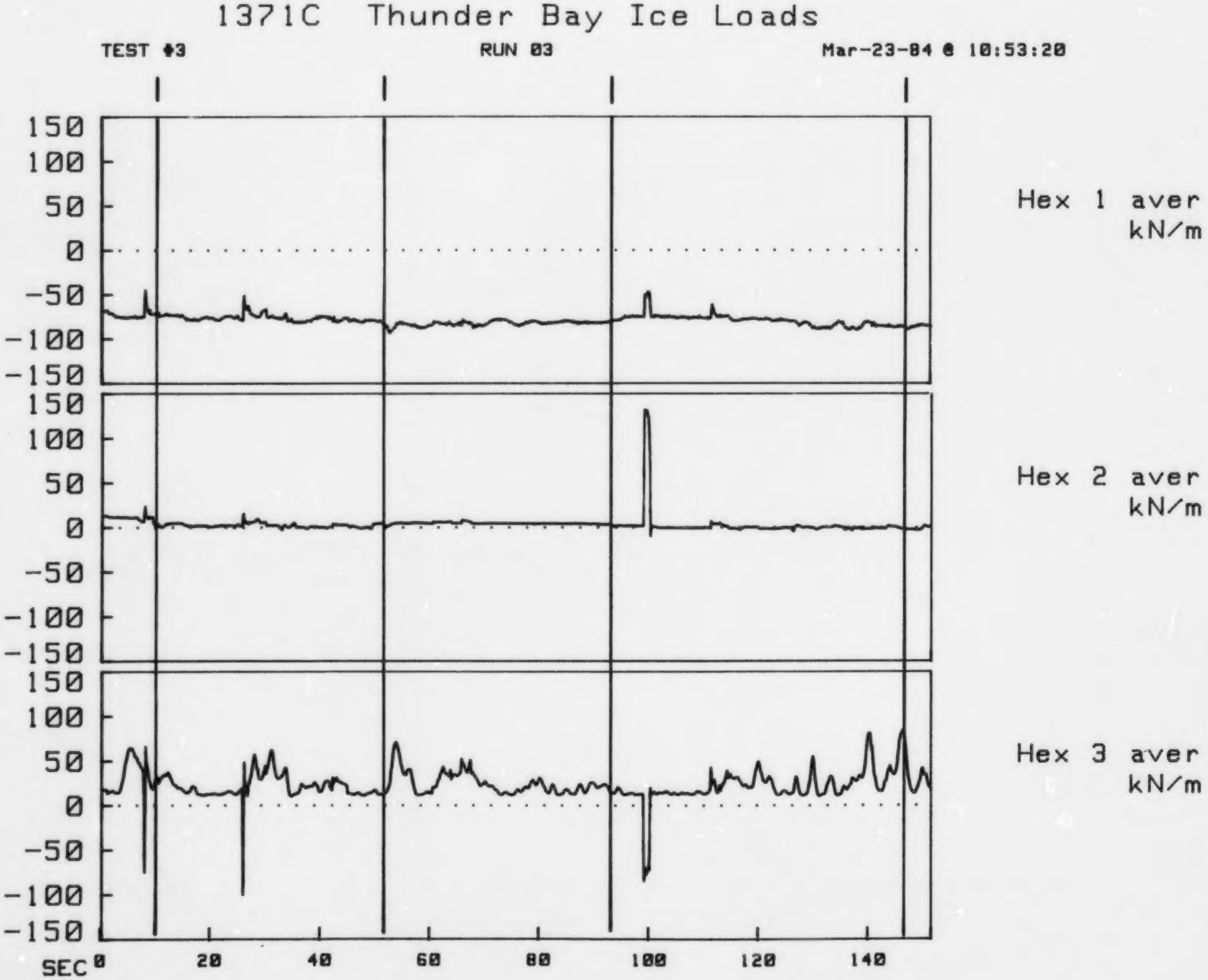
1371C Thunder Bay Ice Loads

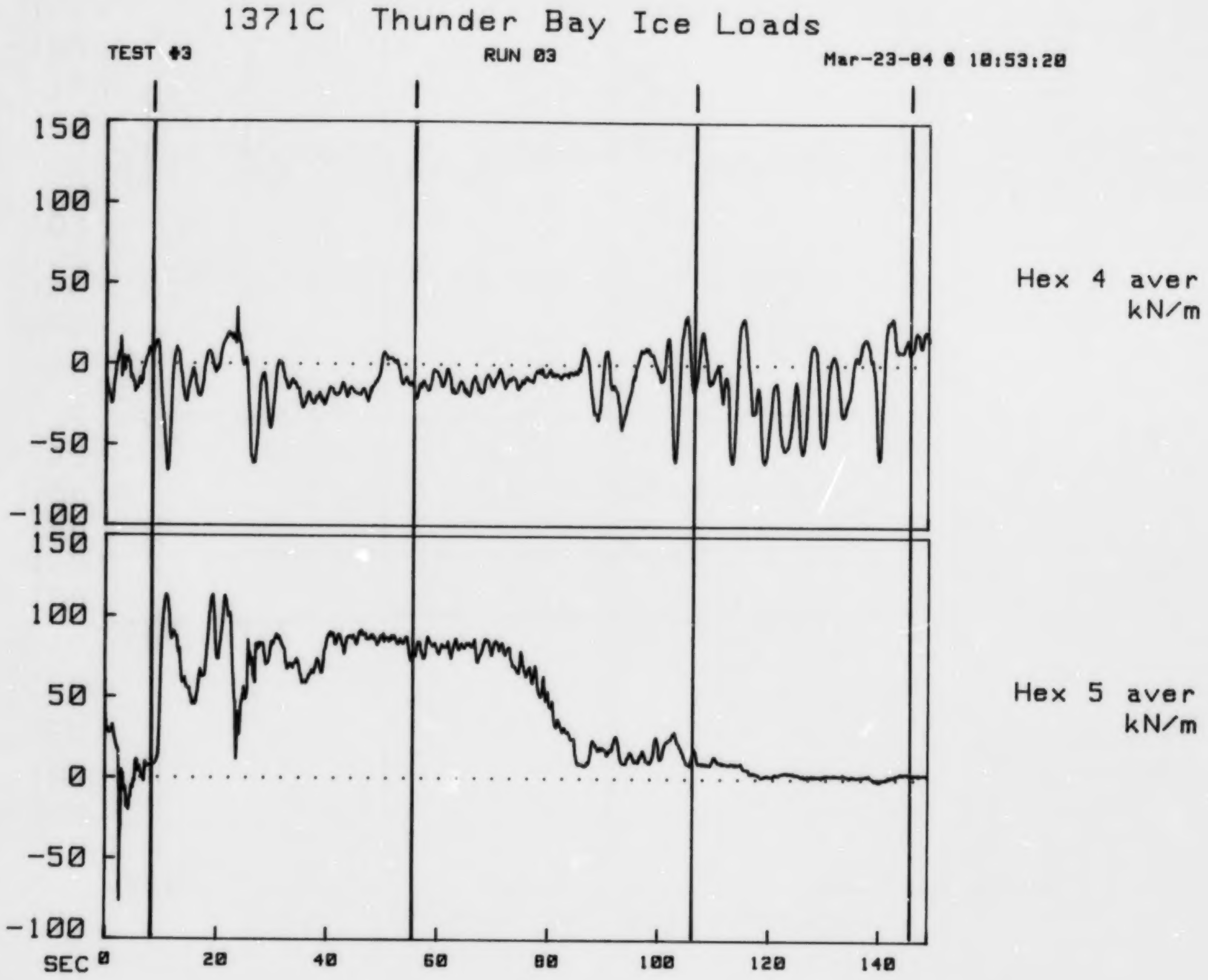
TEST #3 RUN 03 Mar-23-84 @ 18:53:28




1371C Thunder Bay Ice Loads
TEST #3
RUN 03
Mar-23-84 @ 10:53:20
|< 1st >|< 2nd >|< 3rd >|
300
200
100
0
-100
-200
Hexpack 5B
kPa
Hexpack 5C
kPa
Hexpack 5D
kPa
SEC 0
20
40
60
80
100
120
140


1371C Thunder Bay Ice Loads
TEST #3
RUN 03
Mar-23-84 @ 10:53:20
|< 1st >|< 2nd >|< 3rd >|
40
20
0
-20
-40
-60
Hexpack 4
kPa
.10
0.00
-.10
Accel 2
g'S
SEC 0
20
40
60
80
100
120
140


1371C Thunder Bay Ice Loads
TEST #3
RUN 03
Mar-23-84 @ 10:53:20
150
100
50
0
-50
-100
-150
Hex 1 aver
kN/m
Hex 2 aver
kN/m
Hex 3 aver
kN/m
SEC
0
20
40
60
80
100
120
140


1371C Thunder Bay Ice Loads
TEST #3
RUN 03
Mar-23-84 @ 10:53:20
150
100
50
0
-50
-100
150
100
50
0
-50
-100
SEC
0
20
40
60
80
100
120
140
Hex 4 aver
kN/m
Hex 5 aver
kN/m

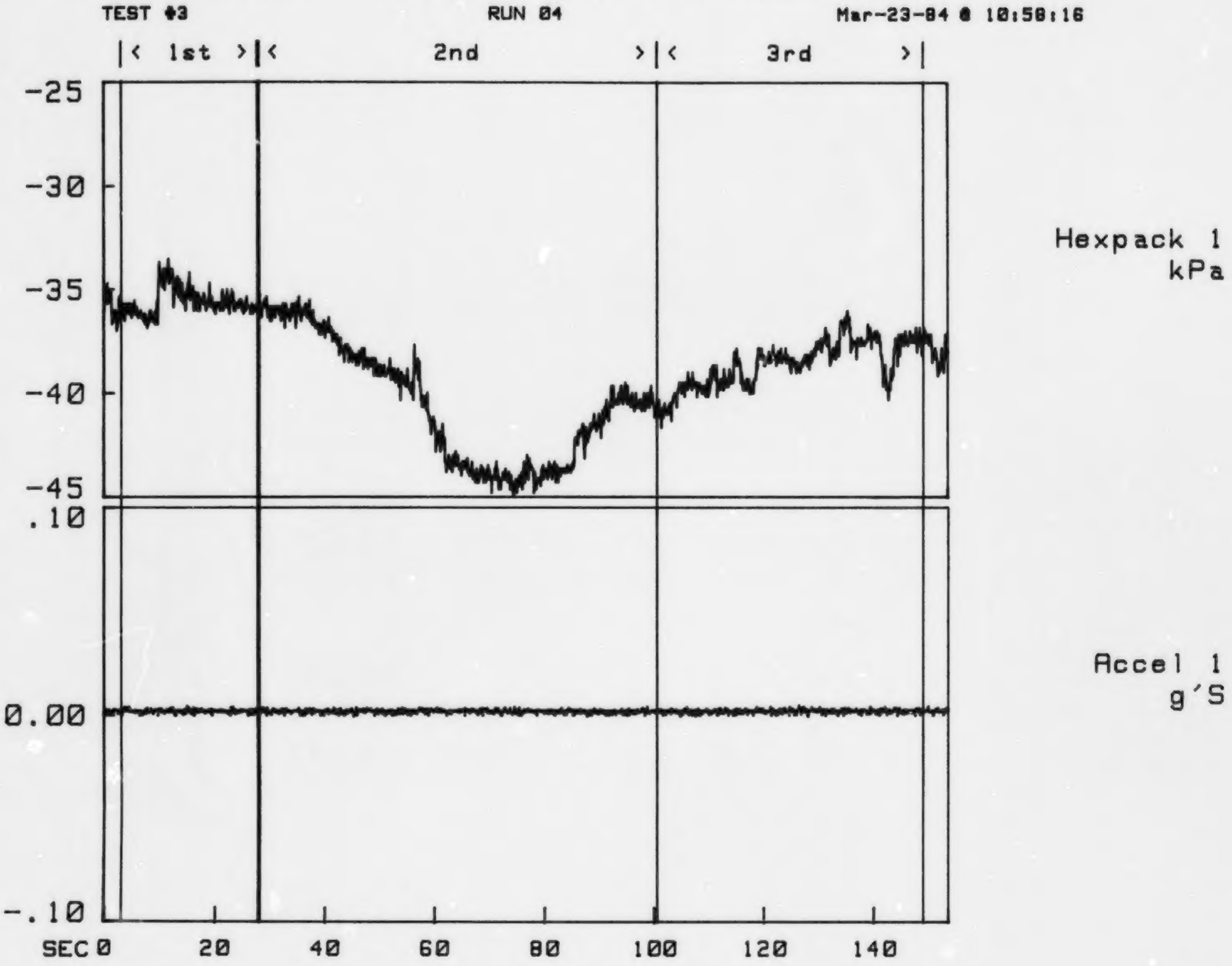
THUNDER BAY ICE LOAD TEST SUMMARY

Test #: 3
Run #: 04
Date: Mar-23-84
Scan Begins at: 10:58:16
Duration of Scan: 150 SEC
Scan ends at: 11:00:46
Type of test: Alexander Henry with ACIB
Location of Ship: Starts 205 m inside dock
Ends 230 m inside dock

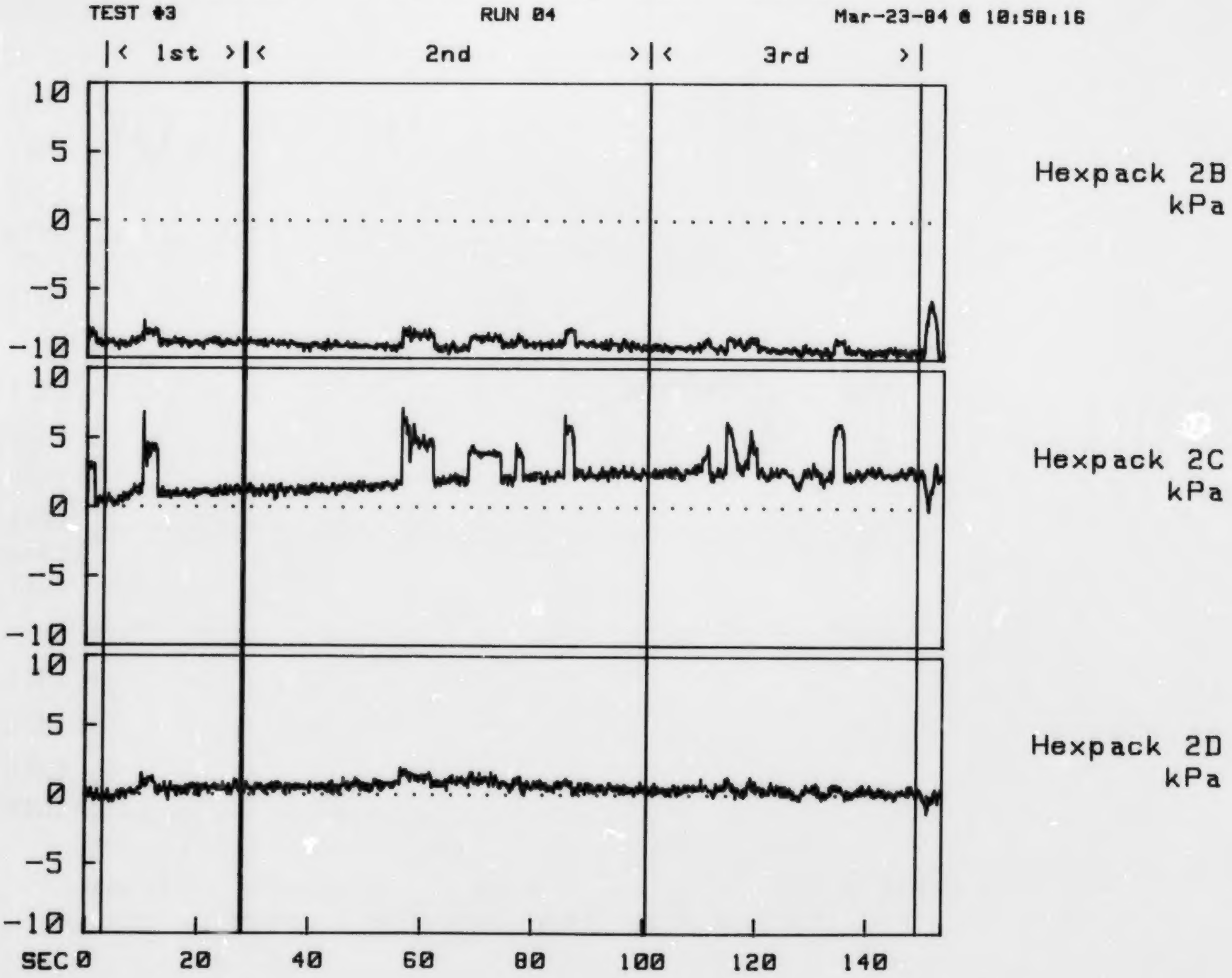
TRANSDUCER	MAXIMUM	MINIMUM	UNITS
Hex 1	-33.53	-44.95	kPa
Accel 1	0.00	0.00	g'S
Hex 2B	-5.59	-9.98	kPa
Hex 2C	3.23	-0.04	kPa
Hex 2D	1.51	-1.29	kPa
Hex 3B	67.25	0.00	kPa
Hex 3C	306.16	-13.07	kPa
Hex 3D	378.96	-21.02	kPa
Hex 4	81.19	-68.21	kPa
Accel 2	0.00	-0.01	g'S
Hex 5B	0.78	-3.15	kPa
Hex 5C	9.28	-0.45	kPa
Hex 5D	4.14	-5.71	kPa
Hex 1 aver	-67.05	-89.90	kN/m
Hex 2 aver	-0.40	-3.51	kN/m
Hex 3 aver	178.09	3.29	kN/m
Hex 4 aver	121.78	-102.32	kN/m
Hex 5 aver	3.95	-2.52	kN/m

Comments: Periodic communication throughout.
Hexpack 3C saturated the analog record.

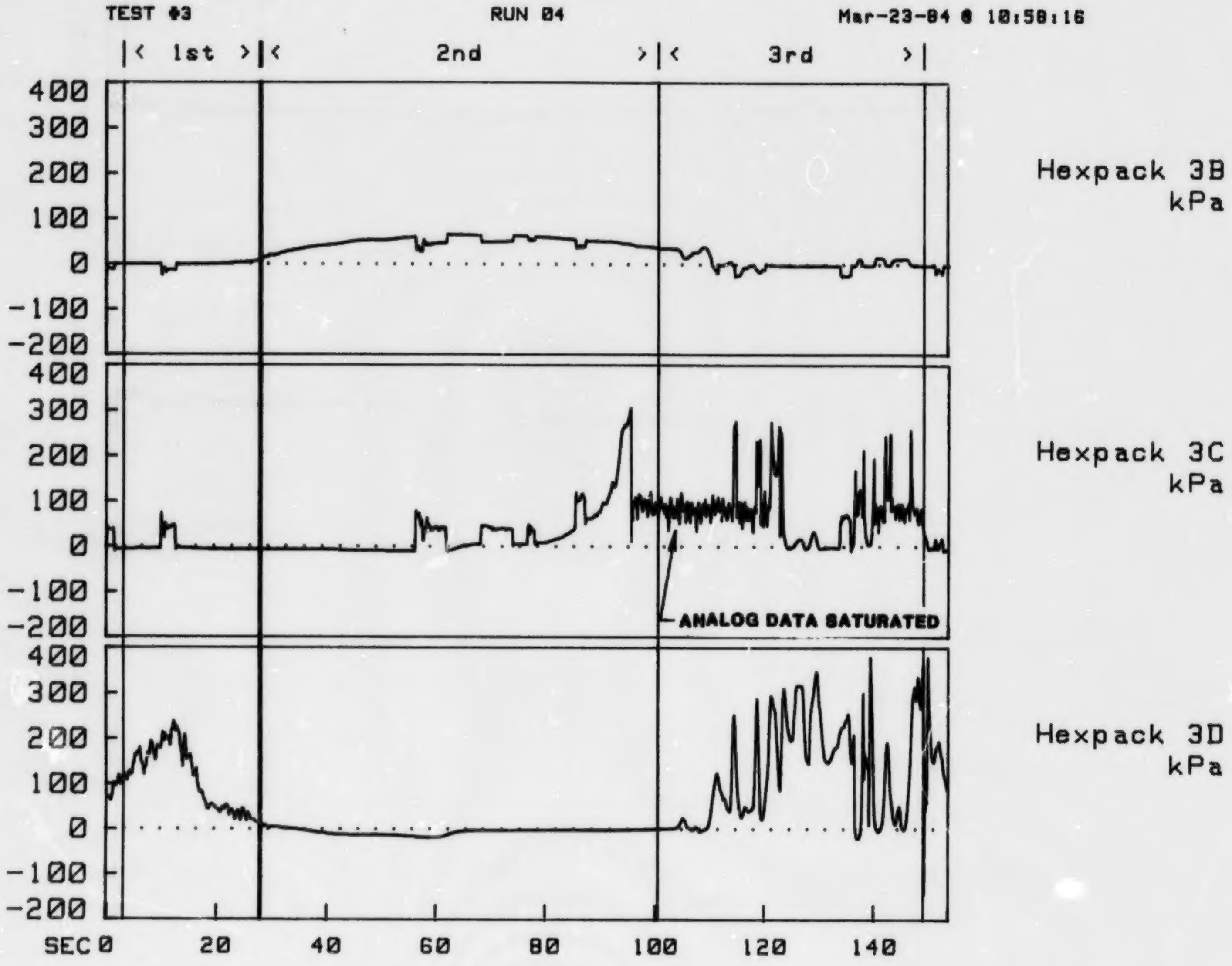
1371C Thunder Bay Ice Loads

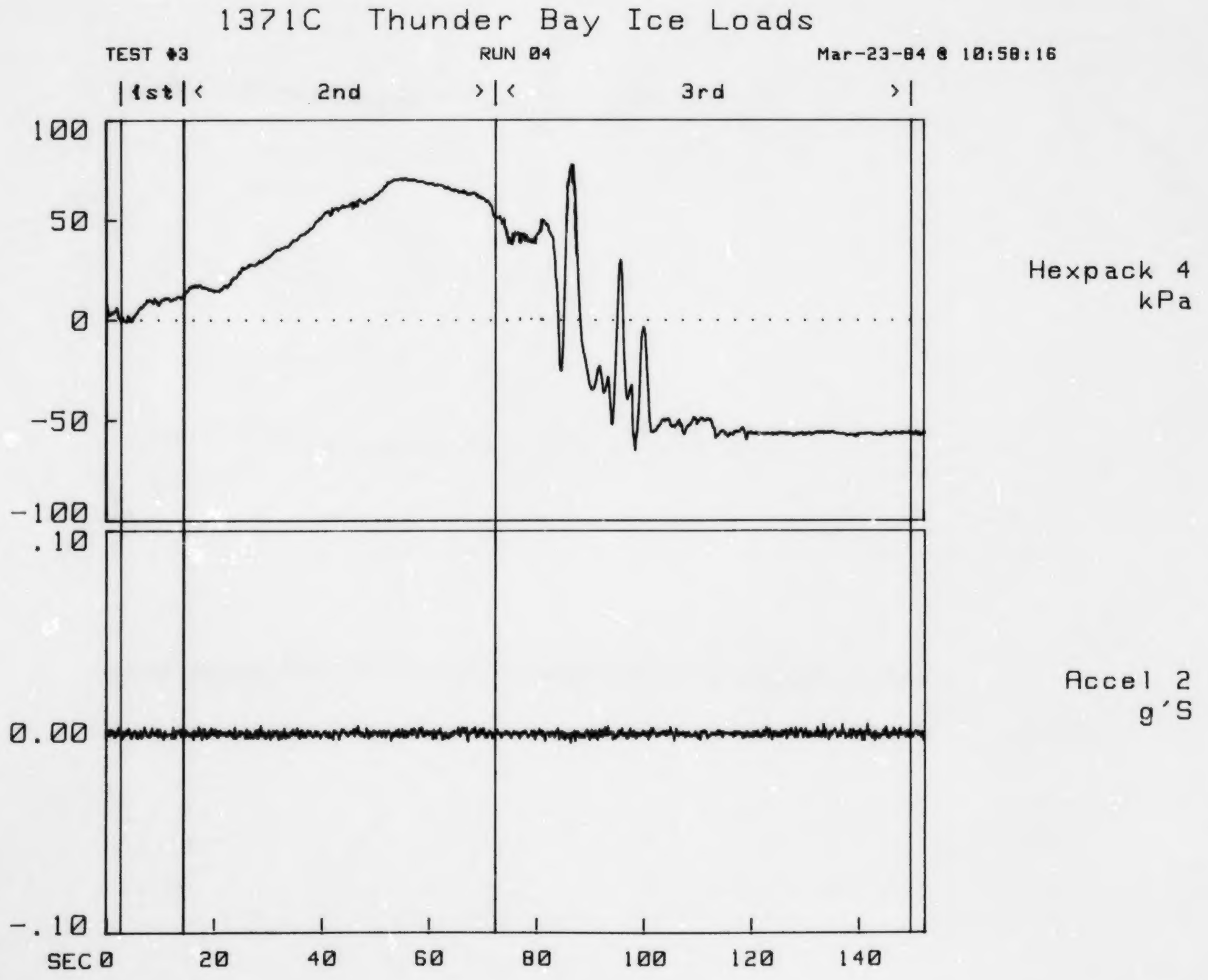


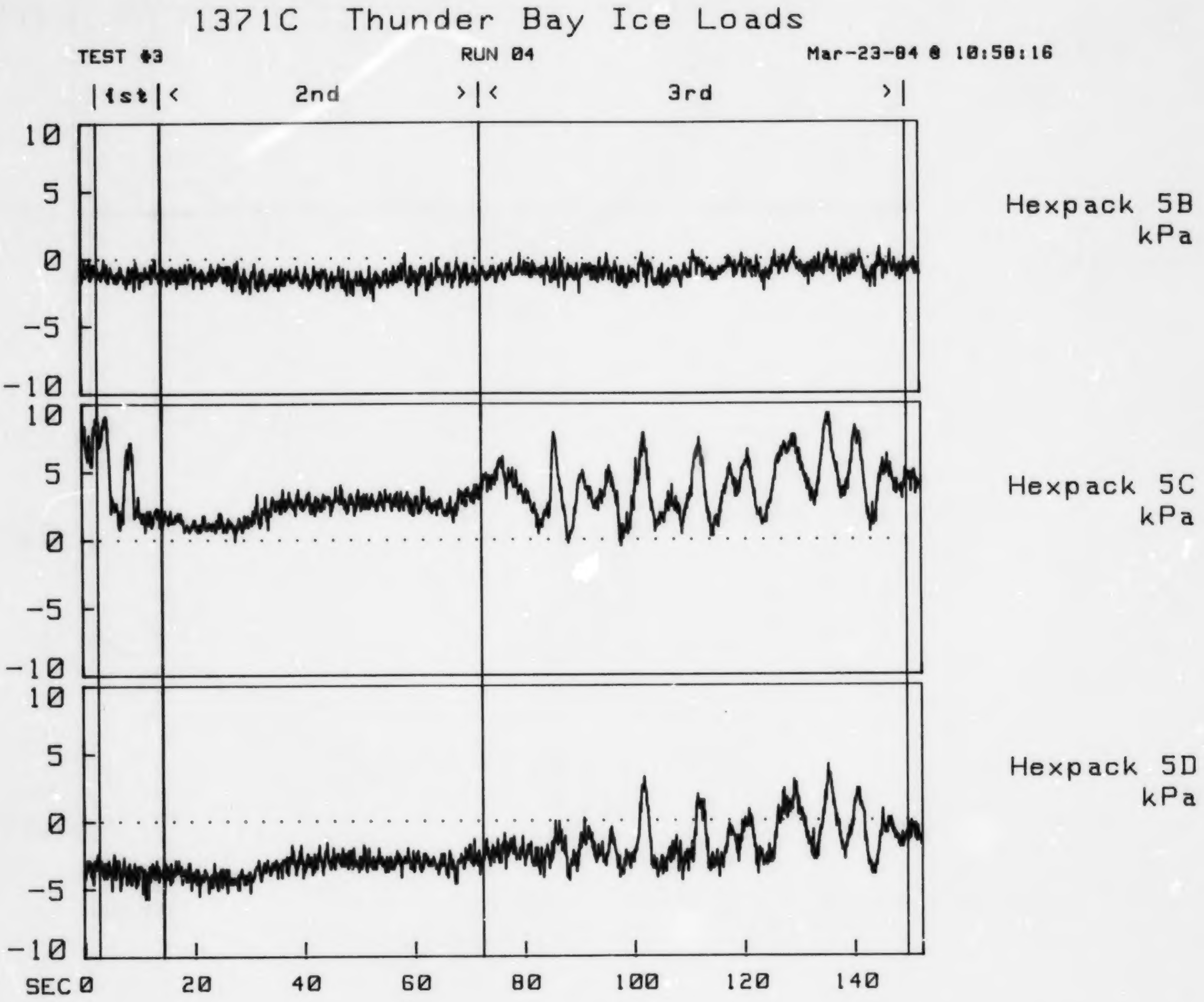
1371C Thunder Bay Ice Loads



1371C Thunder Bay Ice Loads

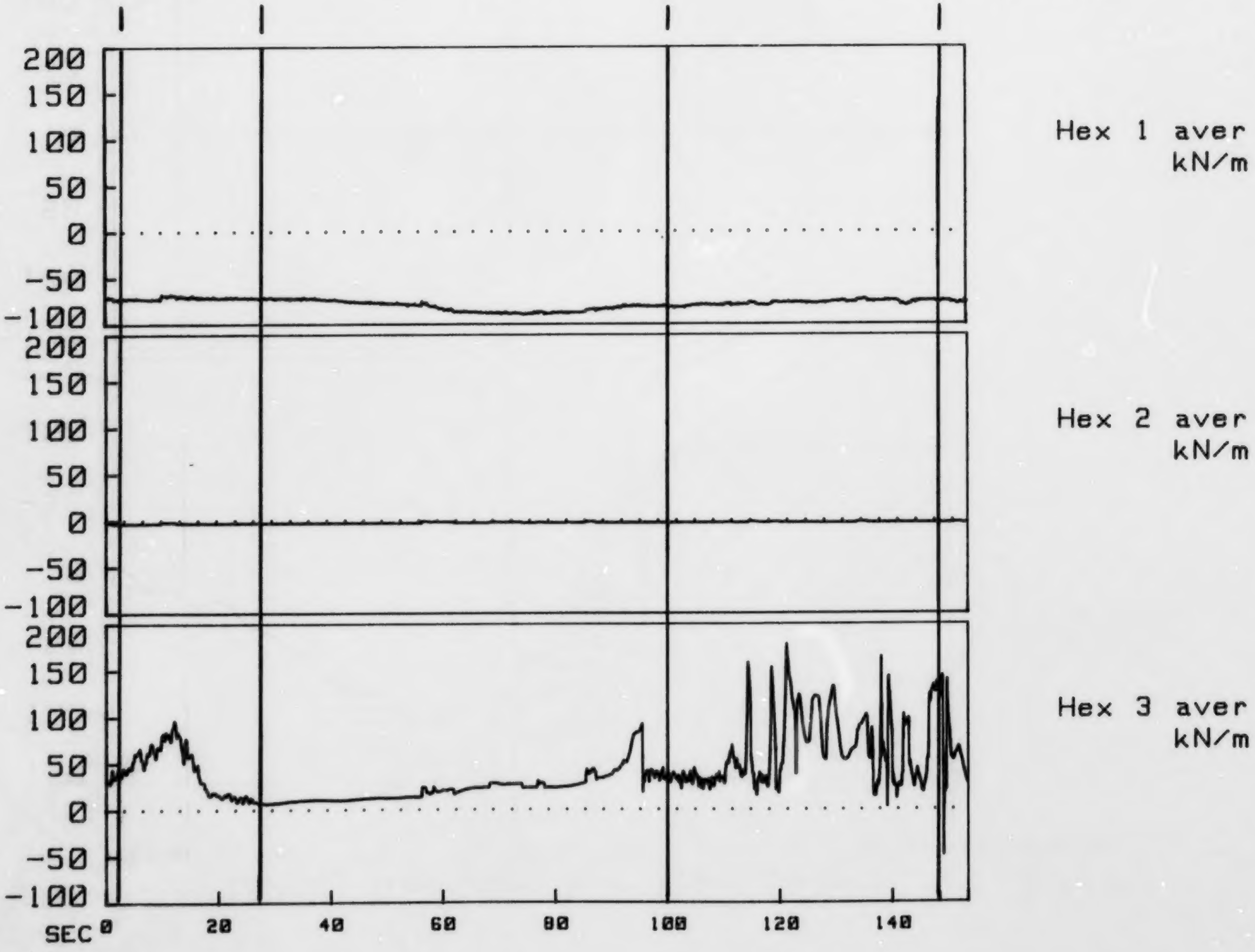


1371C Thunder Bay Ice Loads
TEST #3
RUN 04
Mar-23-84 @ 10:58:16
1st
2nd
3rd
100
50
0
-50
-100
.10
0.00
-.10
SEC 0
20
40
60
80
100
120
140
Hexpack 4
kPa
Accel 2
g'S


1371C Thunder Bay Ice Loads
TEST #3
RUN 04
Mar-23-84 @ 10:58:16
|1st|<
2nd
>|<
3rd
>|
Hexpack 5B
kPa
Hexpack 5C
kPa
Hexpack 5D
kPa
10
5
0
-5
-10
SEC 0
20
40
60
80
100
120
140

1371C Thunder Bay Ice Loads

TEST #3 RUN 04 Mar-23-84 @ 10:58:16



1371C Thunder Bay Ice Loads